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par Victor ABRASHKIN

Résumé. L'analogue local de la conjecture de Grothendieck peut être formulé comme une équivalence entre la catégorie des corps K complets pour une valuation discrete à corps résiduel fini de caractéristique $p \neq 0$ et la catégorie des groupes de Galois absolus des corps K munis de la filtration de ramification. Le cas des corps de caractéristique 0 a été étudié par Mochizuki il y a quelques années. Ensuite, l'auteur de cet article a établi, par une méthode différente l'analogue de la conjecture de Grothendieck dans le cas $p > 2$ (mais K de caractéristique quelconque). Nous proposons ici une modification de cette approche qui inclut le cas $p = 2$ dans la preuve, contient des simplifications considérables et remplace le groupe de Galois par son pro-p-quotient maximal. Une attention particulière est accordée au procédé de la reconstruction de l'isomorphisme de corps à partir d'un isomorphisme de groupe de Galois compatible avec les filtrations de ramification correspondantes.

Abstract. A local analogue of the Grothendieck Conjecture is an equivalence between the category of complete discrete valuation fields K with finite residue fields of characteristic $p \neq 0$ and the category of absolute Galois groups of fields K together with their ramification filtrations. The case of characteristic 0 fields K was studied by Mochizuki several years ago. Then the author of this paper proved it by a different method in the case $p > 2$ (but with no restrictions on the characteristic of K). In this paper we suggest a modified approach: it covers the case $p = 2$, contains considerable technical simplifications and replaces the Galois group of K by its maximal pro-p-quotient. Special attention is paid to the procedure of recovering field isomorphisms coming from isomorphisms of Galois groups, which are compatible with the corresponding ramification filtrations.

Introduction

Throughout this paper p is a prime number. If E is a complete discrete valuation field then we shall assume that its residue field has characteristic

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p. We will consider E to be a subfield of a fixed separable closure E_{sep}. Define $\Gamma_E = \mathrm{Gal}(E_{\mathrm{sep}}/E)$. We denote by $E(p)$ the maximal p-extension of E in E_{sep} and we let $\Gamma_E(p) = \mathrm{Gal}(E(p)/E)$.

Assume that E and E' are complete discrete valuation fields with finite residue fields and there is a continuous field isomorphism $\mu : E \longrightarrow E'$. Then μ can be extended to a field isomorphism $\bar{\mu} : E(p) \longrightarrow E'(p)$. With the conventions about compositions of morphisms which are described at the end of this introduction, the correspondence $\tau \mapsto \bar{\mu}^{-1}\tau\bar{\mu}$ defines a continuous group isomorphism $\bar{\mu}^* : \Gamma_E(p) \longrightarrow \Gamma_{E'}(p)$ such that for any $v \geqslant 0$, $\bar{\mu}^*(\Gamma_E(p)^{(v)}) = \Gamma_{E'}(p)^{(v)}$. Here $\Gamma_E(p)^{(v)}$ is the ramification subgroup of $\Gamma_E(p)$ in the upper numbering.

The principal result of this paper is the following theorem.

Theorem A. *Suppose E and E' are complete discrete valuation fields with finite residue fields and there is a continuous group isomorphism $g : \Gamma_E(p) \longrightarrow \Gamma_{E'}(p)$ such that for all $v \geqslant 0$, $g(\Gamma_E(p)^{(v)}) = \Gamma_{E'}(p)^{(v)}$. Then there is a continuous field isomorphism $\bar{\mu} : E(p) \longrightarrow E'(p)$ such that $\bar{\mu}(E) = E'$ and $g = \bar{\mu}^*$.*

This theorem implies easily a corresponding statement, where the maximal p-extensions $E(p)$ and $E'(p)$ and their Galois groups $\Gamma_E(p)$ and $\Gamma_{E'}(p)$ are replaced, respectively, by the separable closures E_{sep} and E'_{sep} and the Galois groups Γ_E and $\Gamma_{E'}$. Such a statement is known as a local analogue of the Grothendieck Conjecture. Mochizuki [7] proved this local analogue for local fields of characteristic 0. His method is based on an elegant application of Hodge-Tate theory. Under the restriction $p > 2$ the case of local fields of arbitrary characteristic was proved by another method by the author [3]. This proof is based on an explicit description of the ramification subgroups $\Gamma_K(p)^{(v)}$ modulo the subgroup $C_3(\Gamma_K(p))$ of commutators of order $\geqslant 3$ in $\Gamma_K(p)$, where $K = k((t))$, and k is a finite field of characteristic $p > 2$. The restriction $p \neq 2$ appears because the proof uses the equivalence of the category of p-groups and of Lie $\mathbb{Z}_p$-algebras of nilpotent class 2, which holds only under the assumption $p > 2$.

The statement of Theorem A is free from the restriction $p \neq 2$. Its proof follows mainly the strategy from [3] but there are several essential changes.

Firstly, instead of working with the ramification subgroups $\Gamma_K(p)^{(v)}$, $v \geqslant 0$, we fix the simplest possible embedding of $\Gamma_K(p)$ into its Magnus's algebra $\mathcal{A}$ and study the induced fitration by the ideals $\mathcal{A}^{(v)}$, $v \geqslant 0$, of $\mathcal{A}$. As a result, we obtain an explicit description of the ideals $\mathcal{A}^{(v)} \bmod \mathcal{J}^3$, where $\mathcal{J}$ is the augmentation ideal in $\mathcal{A}$. This corresponds to the description of the groups $\Gamma_K(p)^{(v)} \bmod C_3(\Gamma_K(p))$ in [1] but it is easier to obtain and it works for all prime numbers p including $p = 2$.

Secondly, any continuous group automorphism of $\Gamma_K(p)$ which is compatible with the ramification filtration induces a continuous algebra automorphism f of $\mathcal{A}$ such that for any $v \geqslant 0$, $f(\mathcal{A}^{(v)}) = \mathcal{A}^{(v)}$. Similarly to [3], the conditions $f(\mathcal{A}^{(v)}) \operatorname{mod} \mathcal{J}^3 = \mathcal{A}^{(v)} \operatorname{mod} \mathcal{J}^3$ imply non-trivial properties of the restriction of the original automorphism of $\Gamma_K(p)$ to the inertia subgroup $I_K(p)^{\mathrm{ab}}$ of the Galois group of the maximal abelian extension of K. These properties are studied in detail in this paper. This allows us to give a more detailed and effective version of the final stage of the proof of the local analogue of the Grothendieck Conjecture even in the case $p \neq 2$. In particular, this clarifies why it holds with the absolute Galois groups replaced by the Galois groups of maximal p-extensions.

The methods of this paper can be helpful for understanding the relations between fields and their Galois groups in the context of the global Grothendieck Conjecture. For example, suppose F is an algebraic number field, $\bar{F}$ is its algebraic closure, $\Gamma_F = \operatorname{Gal}(\bar{F}/F)$, $\wp$ is a prime divisor in F, $\bar{\wp}$ is its extension to $\bar{F}$ and $F_\wp$, $\bar{F}_{\bar{\wp}}$ are the corresponding completions of F and $\bar{F}$, respectively. Then $\Gamma_{F,\bar{\wp}} = \operatorname{Gal}(\bar{F}_{\bar{\wp}}/F_\wp) \subset \Gamma_F$ is the decomposition group of $\bar{\wp}$. Suppose F is Galois over $\mathbb{Q}$ and $g_\wp : \Gamma_{F,\bar{\wp}} \longrightarrow \Gamma_{F,\bar{\wp}}$ is a continuous group automorphism which is compatible with the ramification filtration on $\Gamma_{F,\bar{\wp}}$. By the local analogue of the Grothendieck Conjecture, $g_\wp$ is induced by a field automorphism $\bar{\mu}_\wp : \bar{F}_{\bar{\wp}} \longrightarrow \bar{F}_{\bar{\wp}}$ such that $\bar{\mu} := \bar{\mu}_{\bar{\wp}}|_{\bar{F}}$ maps $\bar{F}$ to $\bar{F}$ (because $\bar{\mu}(\mathbb{Q}) = \mathbb{Q}$), and, therefore, F to F (because F is Galois over $\mathbb{Q}$). So, $\bar{\mu}$ induces a group automorphism g of Γ_F, which extends the automorphism $g_\wp$ of $\Gamma_{F,\bar{\wp}}$, and we obtain the following criterion:

Criterion. *A group automorphism $g_\wp \in \operatorname{Aut}\Gamma_{F,\bar{\wp}}$ can be extended to a group automorphism $g \in \operatorname{Aut}\Gamma_F$ if and only if $g_\wp$ is compatible with the ramification filtration on $\Gamma_{F,\bar{\wp}}$.*

It would be interesting to understand how “global” information about the embedding of $\Gamma_{F,\wp}$ into Γ_F is reflected in “local” properties of the ramification filtration of $\Gamma_{F,\bar{\wp}}$.

Everywhere in the paper we use the following agreement about compositions of morphisms: if $f : A \longrightarrow B$ and $g : B \longrightarrow C$ are morphisms then their composition will be denoted by fg, in other words, if $a \in A$ then $(fg)(a) = g(f(a))$. One of the reasons is that when operating on morphisms (rather than on their values in $a \in A$) the notation fg reflects much better the reality that it is the composition of the first morphism f and the second one g.

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1. An analogue of the Magnus algebra for $\Gamma(p)$

In this section $K = k((t_K))$ is the local field of formal Laurent series with residue field $k = \mathbb{F}_{q_0}$, where $q_0 = p^{N_0}$, $N_0 \in \mathbb{N}$, and t_K is a fixed uniformiser of K (in most cases t_K will be denoted just by t). We fix a choice of a separable closure K_{sep} of K, denote by $K(p)$ the maximal p-extension of K in K_{sep} and set $\Gamma = \mathrm{Gal}(K_{\mathrm{sep}}/K)$, $\Gamma(p) = \mathrm{Gal}(K(p)/K)$.

1.1. Liftings. Notice first, that the uniformiser t_K of K can be taken as a p-basis for any finite extension L of K in K_{sep}. For $M \in \mathbb{N}$, set

$$O_M(L) = W_M(\sigma^{M-1}L)[t_{K,M}] \subset W_M(L),$$

where W_M is the functor of Witt vectors of length M, σ is the p-th power map and $t_{K,M} = [t_K] = (t_K, 0, \dots, 0) \in W_M(L)$ is the Teichmüller representative of t_K. Very often we shall use the simpler notation t for $t_{K,M}$ (as well as for t_K). $O_M(L)$ is a lifting of L modulo p^M or, in other words, it is a flat $W_M(\mathbb{F}_p)$-module such that $O_M(L) \bmod p = L$. This is a special case of the construction of liftings in [4].

Let $O_M(K_{\mathrm{sep}})$ be the inductive limit of all $O_M(L)$, where $L \subset K_{\mathrm{sep}}$, $[L : K] < \infty$. Then we have a natural action of Γ on $O_M(K_{\mathrm{sep}})$ and $O_M(K_{\mathrm{sep}})^\Gamma = O_M(K) = W_M(k)((t))$. We shall use again the notation σ for the natural extension of σ to $O_M(K_{\mathrm{sep}})$. Clearly, $O_M(K_{\mathrm{sep}})|_{\sigma=\mathrm{id}} = W_M(\mathbb{F}_p)$. Introduce the absolute liftings $O(K) = \varprojlim_M O_M(K)$ and $O(K_{\mathrm{sep}}) = \varprojlim_M O_M(K_{\mathrm{sep}})$. Again we have $O(K_{\mathrm{sep}})^\Gamma = O(K)$ and $O(K_{\mathrm{sep}})|_{\sigma=\mathrm{id}} = W(\mathbb{F}_p)$. We can also consider the liftings $O_M(K(p))$ and $O(K(p))$ with the natural action of $\Gamma(p)$ and similar properies.

Notice that for any $j \in O(K(p))$ there is an $i \in O(K(p))$ such that $\sigma(i) - i = j$.

1.2. The algebra $\mathcal{A}$. Set $\mathbb{Z}(p) = \{a \in \mathbb{N} \mid (a, p) = 1\}$ and $\mathbb{Z}^0(p) = \mathbb{Z}(p) \cup \{0\}$. Let $\mathcal{A}_k$ be the profinite associative $W(k)$-algebra with the set of pro-free generators $\{D_{an} \mid a \in \mathbb{Z}(p), n \in \mathbb{Z} \bmod N_0\} \cup \{D_0\}$.

This means that $\mathcal{A}_k = \varprojlim_{C,M} \mathcal{A}_{CMk}$, where $C, M \in \mathbb{N}$,

$$\mathcal{A}_{CMk} = W_M(k)[[\{D_{an} \mid a \leqslant C, n \in \mathbb{Z} \bmod N_0\}]]$$

and the connecting morphisms $\mathcal{A}_{C_1M_1k} \longrightarrow \mathcal{A}_{C_2M_2k}$ are defined for $C_1 \geqslant C_2$, $M_1 \geqslant M_2$ and induced by the correspondences $D_{an} \mapsto 0$ if $C_2 < a \leqslant C_1$ and $D_{an} \mapsto D_{an}$ if $a \leqslant C_2$, and by the morphism $W_{M_1}(k) \longrightarrow W_{M_2}(k)$ of reduction modulo p^{M_2}.

Denote again by σ the extension of the automorphism σ of $W(k)$ to $\mathcal{A}_k$ via the correspondences $\sigma : D_{an} \mapsto D_{a,n+1}$, where $a \in \mathbb{Z}(p)$, $n \in \mathbb{Z} \bmod N_0$, and the correspondence $D_0 \mapsto D_0$. Then $\mathcal{A} := \mathcal{A}_k|_{\sigma=\mathrm{id}}$ is a pro-free $\mathbb{Z}_p$-algebra: if $\beta_1,\dots,\beta_{N_0}$ is a $\mathbb{Z}_p$-basis of $W(k)$ and, for $a\in\mathbb{Z}(p)$ and $1\leqslant r\leqslant N_0$,

$$D_a^{(r)}:=\sum_{n\in\mathbb{Z}\bmod N_0}\sigma^n(\beta_r)D_{an},$$

then $\{D_a^{(r)}\mid a\in\mathbb{Z}(p),1\leqslant r\leqslant N_0\}\cup\{D_0\}$ is a set of pro-free generators of $\mathcal{A}$. Notice also that if $\alpha_1,\dots,\alpha_{N_0}\in W(k)$ is a dual basis for $\beta_1,\dots,\beta_{N_0}$ (i.e. $\mathrm{Tr}(\alpha_i\beta_j)=\delta_{ij}$, where $1\leqslant i,j\leqslant N_0$ and Tr is the trace of the field extension $W(k)\otimes\mathbb{Q}_p$ over $\mathbb{Q}_p$) then for any $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\bmod N_0$, it holds

$$D_{an}=\sum_{1\leqslant r\leqslant N_0}\sigma^n(\alpha_r)D_a^{(r)}.$$

Denote by $\mathcal{J}$, resp. $\mathcal{J}_{CM}$, the augmentation ideal in $\mathcal{A}$, resp. $\mathcal{A}_{CM}$. Set $\mathcal{A}_K:=\mathcal{A}\hat{\otimes}O(K)$, $\mathcal{A}_{CMK}=\mathcal{A}_{CM}\hat{\otimes}O(K)$, $\mathcal{A}_{K(p)}=\mathcal{A}\hat{\otimes}O(K(p))$. We shall also use similar notation in other cases of extensions of scalars, e.g. $\mathcal{J}_k=\mathcal{J}\hat{\otimes}W(k)$, $\mathcal{J}_K=\mathcal{J}\hat{\otimes}O(K)$, $\mathcal{J}_{K(p)}=\mathcal{J}\hat{\otimes}O(K(p))$.

1.3. The embeddings ψ_f. Take $\alpha_0\in W(k)$ such that $\mathrm{Tr}(\alpha_0)=1$, where again Tr is the trace of the field extension $W(k)\otimes\mathbb{Q}_p\supset\mathbb{Q}_p$. For all $n\in\mathbb{Z}\bmod N_0$, set $D_{0n}=\sigma^n(\alpha_0)D_0$ and introduce the element

$$e=1+\sum_{a\in\mathbb{Z}^0(p)}t^{-a}D_{a0}\in 1+\mathcal{J}_K.$$

We shall use the same notation e for the projections of e to any of $\mathcal{A}_{CMK}\bmod\mathcal{J}^n_{CMK}$, where $C,M,n\in\mathbb{N}$.

Proposition 1.1. *There is an $f\in 1+\mathcal{J}_{K(p)}$ such that $\sigma(f)=fe$.*

Proof. For $C,M,n\in\mathbb{N}$, set

$$S_{CMn}=\left\{f\in 1+\mathcal{J}_{CMK(p)}\bmod\mathcal{J}^n_{CMK(p)}\mid\sigma f=fe\bmod\mathcal{J}^n_{CMK(p)}\right\}.$$

We use induction on $n\in\mathbb{N}$ to prove that for all $C,M,n\in\mathbb{N}$, $S_{CMn}\neq\emptyset$.

Clearly, $S_{CM1}=\{1\}\neq\emptyset$.

Suppose that $S_{CMn}\neq\emptyset$ and $f\in S_{CMn}$. Then $\sigma(f)=fe\bmod\mathcal{J}^n_{CMK(p)}$. Let

$$\pi:1+\mathcal{J}_{CMK(p)}\bmod\mathcal{J}^{n+1}_{CMK(p)}\longrightarrow 1+\mathcal{J}_{CMK(p)}\bmod\mathcal{J}^n_{CMK(p)}$$

be the natural projection. If $f_1\in 1+\mathcal{J}_{CMK(p)}\bmod\mathcal{J}^{n+1}_{CMK(p)}$ is such that $\pi(f_1)=f$ then $\sigma(f_1)=f_1e+j\bmod\mathcal{J}^{n+1}_{CMK(p)}$, where $j\in\mathcal{J}^n_{CMK(p)}$. There is an $i\in\mathcal{J}^n_{CMK(p)}$ such that $\sigma(i)-i=j$, cf. n.1.1. Therefore,

$$\sigma(f_1-i)=f_1e+j-(i+j)=(f_1-i)e\bmod\mathcal{J}^{n+1}_{CMK(p)},$$

using that $ie=i\bmod\mathcal{J}^{n+1}_{CMK(p)}$, and $S_{CM,n+1}\neq\emptyset$ because it contains f_1-i.

Notice that each S_{CMn} is a finite set and each $f \in S_{CMn}$ has a finite field of definition. This follows from the fact that for any $C, M, n \in \mathbb{N}$, the $\mathbb{Z}_p$-module $\mathcal{A}_{CM} \bmod \mathcal{J}_{CM}^n$ has finitely many free generators and, therefore, the equation $\sigma f = fe$ is equivalent to finitely many usual polynomial equations. Also notice that $\{S_{CMn} \mid C, M, n \in \mathbb{N}\}$ has a natural structure of projective system. Therefore, $\varprojlim_{C,M,n} CMn \neq \emptyset$, and any element f of this projective limit satisfies $f \in 1 + \mathcal{J}_{K(p)}$ and $\sigma(f) = fe$.

The proposition is proved. □

For any $f \in 1 + \mathcal{J}_{K(p)}$ such that $\sigma(f) = fe$ and $\tau \in \Gamma(p)$, set $\psi_f(\tau) = (\tau f)f^{-1}$. Clearly, $\sigma(\psi_f(\tau)) = \tau(\sigma f)(\sigma f)^{-1} = (\tau f)ee^{-1}f = \psi_f(\tau)$. Therefore, $\psi_f(\tau) \in (1 + \mathcal{J}_{K(p)})|_{\sigma=\mathrm{id}} = 1 + \mathcal{J}$.

Proposition 1.2. a) *ψ_f is a closed group embedding of $\Gamma(p)$ into $(1+\mathcal{J})^\times$.*
b) *ψ_f induces an isomorphism ψ_f^{ab} of the topological groups $\Gamma(p)^{\mathrm{ab}}$ and $(1 + \mathcal{J})^\times \bmod \mathcal{J}^2$.*
c) *If $f_1 \in 1 + \mathcal{J}_{K(p)}$ is such that $\sigma(f_1) = f_1 e$ then there is an element $c \in 1 + \mathcal{J}$ such that for any $\tau \in \Gamma(p)$, $\psi_{f_1}(\tau) = c\psi_f(\tau)c^{-1}$.*
d) *ψ_f induces an embedding of the group of all continuous automorphisms $\mathrm{Aut}\Gamma(p)$ into the group $\mathrm{Aut}\mathcal{A}$ of continuous automorphisms of the $\mathbb{Z}_p$-algebra $\mathcal{A}$.*

Proof. a) Clearly, ψ_f can be treated as a pro-p-version of the embedding of the group $\Gamma(p)$ into its Magnus algebra. Therefore, by [8], Ch 1, Sec 6, ψ_f induces, for all $n \in \mathbb{N}$, the closed embeddings of the quotients $C_n(\Gamma(p))/C_{n+1}(\Gamma(p))$ of commutator subgroups in $\Gamma(p)$ into $1 + \mathcal{J}^n \bmod \mathcal{J}^{n+1}$. This implies that ψ_f induces, for all $n \geqslant 1$, the closed group embeddings of $\Gamma(p)/C_n(\Gamma(p))$ into $1 + \mathcal{J} \bmod \mathcal{J}^n$, and therefore, ψ_f is a closed group monomorphism.

b) Consider the profinite $\mathbb{Z}_p$-basis $\{D_a^{(r)} \mid a \in \mathbb{Z}(p), 1 \leqslant r \leqslant N_0\} \cup \{D_0\}$ for $\mathcal{J} \bmod \mathcal{J}^2$ from n.1.2. For $1 \leqslant r \leqslant N_0$, as earlier, consider $\alpha_r \in W(k)$, which form the dual basis of the basis $\{\beta_r \mid 1 \leqslant r \leqslant N_0\}$ chosen in n.1.2 to define the generators $D_a^{(r)}$. Then

$$e = 1 + \sum_{1 \leqslant r \leqslant N_0 a \in \mathbb{Z}(p)} \alpha_r t^{-a} D_a^{(r)} + \alpha_0 D_0$$

and

$$f = 1 + \sum_{1 \leqslant r \leqslant N_0 a \in \mathbb{Z}(p)} f_a^{(r)} D_a^{(r)} + f_0 D_0 \bmod \mathcal{J}_{K(p)}^2,$$

where for $1 \leqslant r \leqslant N_0$ and $a \in \mathbb{Z}(p)$, $f_a^{(r)}$ and f_0 belong to $O(K(p)) \subset W(K(p))$ and satisfy the equations $\sigma f_a^{(r)} - f_a^{(r)} = \alpha_r t^{-a}$ and $\sigma f_0 - f_0 = \alpha_0$.

Then for any $\tau\in\Gamma(p)$,

$$\psi_f(\tau)=1+\sum_{a,r}(\tau f_a^{(r)}-f_a^{(r)})D_a^{(r)}+(\tau f_0-f_0)D_0 \bmod \mathcal{J}^2_{K(p)}$$

and the identification $\psi_f:\Gamma(p)^{\mathrm{ab}}\simeq(1+\mathcal{J})^\times \bmod \mathcal{J}^2$ is equivalent to the identifications of Witt-Artin-Schreier theory

$$\oplus_{a\in\mathbb{Z}(p)}W(k)t^{-a}\oplus W(\mathbb{F}_p)\alpha_0=O(K)/(\sigma-\mathrm{id})O(K)=\mathrm{Hom}_{\mathrm{cts}}(\Gamma(p),W(\mathbb{F}_p)).$$

c) Clearly, $\sigma(f_1f^{-1})=\sigma(f_1)\sigma(f)^{-1}=f_1ee^{-1}f^{-1}=f_1f^{-1}$. Therefore,

$$f_1f^{-1}=c\in(1+\mathcal{J}_{K(p)})\cap\mathcal{A}=1+\mathcal{J}$$

and for any $\tau\in\Gamma(p)$,

$$\psi_{f_1}(\tau)=\tau(f_1)f_1^{-1}=\tau(cf)(cf)^{-1}=c(\tau f)f^{-1}c^{-1}=c\psi_f(\tau)c^{-1}.$$

d) This also follows from the above mentioned interpretation of $\mathcal{A}$ as a profinite analogue of the Magnus algebra for $\Gamma(p)$. □

1.4. The identification $\boldsymbol{\psi_f^{\mathrm{ab}}}$. As it was already mentioned in the proof of proposition 1.2 the identification ψ_f^{ab} comes from the isomorphism of Witt-Artin-Schreier theory

$$\Gamma(p)^{\mathrm{ab}}=\mathrm{Hom}(O(K)/(\sigma-\mathrm{id})O(K),W(\mathbb{F}_p))$$

and does not depend on the choice of $t=t_K$ and $f\in 1+\mathcal{J}_{K(p)}$. Suppose $\tau_0\in\Gamma(p)^{\mathrm{ab}}$ is such that $\psi_f^{\mathrm{ab}}(\tau_0)=1+D_0$ and for $a\in\mathbb{Z}(p)$ and $1\leqslant r\leqslant N_0$, the elements $\tau_a^{(r)}\in\Gamma(p)^{\mathrm{ab}}$ are such that $\psi_f^{\mathrm{ab}}(\tau_a^{(r)})=1+D_a^{(r)} \bmod \mathcal{J}^2$. Then the element

$$e=1+\alpha_0D_0+\sum_{a,r}\alpha_rt^{-a}D_a^{(r)}$$

corresponds to the diagonal element $\alpha_0\otimes\tau_0+\sum_{a,r}\alpha_rt^{-a}\otimes\tau_a^{(r)}$ from $O(K)\otimes\Gamma(p)^{\mathrm{ab}}=$

$$O(K)\otimes\mathrm{Hom}(O(K)/(\sigma-\mathrm{id})O(K),\mathbb{Z}_p)=\mathrm{Hom}(O(K)/(\sigma-\mathrm{id})O(K),O(K)),$$

which comes from the following natural embedding

$$O(K)/(\sigma-\mathrm{id})O(K)=\oplus_{a\in\mathbb{Z}(p)}W(k)t^{-a}\oplus W(\mathbb{F}_p)\alpha_0\subset O(K).$$

The above elements τ_0, resp. $\tau_a^{(r)}$, correspond to t, resp. $E(\beta_r,t^a)^{1/a}$, by the reciprocity map of local class field theory. (Here $\beta_1,\dots,\beta_{N_0}\in W(k)$ were chosen in n.1.2 and for $\beta\in W(k)$,

$$E(\beta,X)=\exp(\beta X+(\sigma\beta)X^p/p+\dots+(\sigma^n\beta)X^{p^n}/p^n+\dots)\in W(k)[[X]]$$

is the generalisation of the Artin-Hasse exponential introduced by Shafarevich [9].) This fact follows from the Witt explicit reciprocity law, cf. [5]. Then the elements D_{an}, where $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\operatorname{mod}N_0$, correspond to

$$\sum_{1\leqslant r\leqslant N_0}\sigma^n(\alpha_r)\otimes E(\beta_r,t^a)^{1/a}\in W(k)\otimes_{\mathbb{Z}_p}\mathcal{G}_a,$$

where the (multiplicative) group $\mathcal{G}_a:=\{E(\gamma,t^a)\mid\gamma\in W(k)\}$ is identified with the $\mathbb{Z}_p$-module of Witt vectors $W(k)$ via the map $E(\gamma,t^a)^{1/a}\mapsto\gamma$. Consider the identification

$$W(k)\otimes_{\mathbb{Z}_p}W(k)=\oplus_{m\in\mathbb{Z}\operatorname{mod}N_0}W(k)_m$$

given by the correspondence $\alpha\otimes\beta\mapsto\{\sigma^{-m}(\alpha)\beta\}_{m\in\mathbb{Z}\operatorname{mod}N_0}$. Under this identification the element D_{an} corresponds to the vector $\delta_n\in\oplus_m W(k)_m$, which has n-th coordinate 1 and all remaining coordinates 0. This interpretation of the generators D_{an} will be applied below in the following situation. Suppose $[k':k]<\infty$, $k'\simeq\mathbb{F}_{q_0'}$ with $q_0'=p^{N_0'}$. Clearly, $N_0'\equiv 0\operatorname{mod}N_0$. For $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\operatorname{mod}N_0'$ denote by D'_{an} an analogue of D_{an} constructed for $K'=k'((t_{K'}))$ with $t_{K'}=t$. Let $\Gamma'=\operatorname{Gal}(K_{\rm sep}/K')$ and let $\Gamma'(p)$ be the Galois group of the maximal p-extension $K'(p)$ of K' in $K_{\rm sep}$. With the above notation we have the following property:

Proposition 1.3. *For any $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\operatorname{mod}N_0'$, D'_{an} is mapped to $D_{a,n\operatorname{mod}N_0}$ under the map $\Gamma'(p)^{\rm ab}\longrightarrow\Gamma(p)^{\rm ab}$, which is induced by the natural embedding $\Gamma'\subset\Gamma$.*

2. Action of analytic automorphisms on $I^{\rm ab}(p)$

As earlier, $K=k((t))$, $k\simeq\mathbb{F}_{q_0}$ with $q_0=p^{N_0}$ and $\Gamma(p)=\operatorname{Gal}(K(p)/K)$. Let $I(p)$ be the inertia subgroup of $\Gamma(p)$ and let $I(p)^{\rm ab}$ be its image in the maximal abelian quotient $\Gamma(p)^{\rm ab}$ of $\Gamma(p)$.

2.1. Consider the group $\operatorname{Aut}K$ of continuous field automorphisms of K. Let $\operatorname{Fr}(t)\in\operatorname{Aut}K$ be such that $\operatorname{Fr}(t)|_k=\sigma$ and $\operatorname{Fr}(t):t\mapsto t$. Then any element of $\operatorname{Aut}K$ is the composition of a power $\operatorname{Fr}(t)^n$, where $n\in\mathbb{Z}\operatorname{mod}N_0$, and a field automorphism from $\operatorname{Aut}^0(K):=\{\eta\in\operatorname{Aut}K\mid\eta|_k=\mathrm{id}\}$. Notice that any $\eta\in\operatorname{Aut}^0K$ is uniquely determined by the image $\eta(t)$ of t, which is again a uniformizer in K.

Let $\operatorname{Aut}_K K(p)$ be the group of continuous automorphisms $\bar\eta$ of $K(p)$ such that $\bar\eta|_K\in\operatorname{Aut}K$. Then $\operatorname{Aut}_K K(p)$ acts on $\Gamma(p)$: if $\bar\eta\in\operatorname{Aut}_K K(p)$ and $\tau\in\Gamma(p)$ then the action of $\bar\eta$ is given by the correspondence $\tau\mapsto\bar\eta^*(\tau)=\bar\eta^{-1}\tau\bar\eta$, i.e. $\bar\eta^*(\tau):K(p)\xrightarrow{\bar\eta^{-1}}K(p)\xrightarrow{\tau}K(p)\xrightarrow{\bar\eta}K(p)$, cf. the introduction for the agreement about compositions of maps. The action induced by $\bar{\eta}^* \in \mathrm{Aut}_K K(p)$ on $\Gamma(p)^{\mathrm{ab}}$ depends only on $\eta := \bar{\eta}|_K$ and will be denoted simply by η^*.

2.2. Let $\mathcal{M} = I(p)^{\mathrm{ab}} \otimes \mathbb{F}_p$. If U_K is the group of principal units in K then we shall use the identification $\mathcal{M} = U_K/U_K^p$, which is given by the reciprocity map of local class field theory. Notice that, with respect of this identification, for any $\eta \in \mathrm{Aut}K$, the action η^* comes from the natural action of η on K. We shall denote the k-linear extension of the action of η to $\mathcal{M}_k := \mathcal{M} \otimes_{\mathbb{F}_p} k$ by the same symbol η^*.

Use the map $m \mapsto (\psi_f^{\mathrm{ab}}(m) - 1) \bmod p$ to identify $\mathcal{M}_k$ with a submodule of $\mathcal{J}_k \bmod (p, \mathcal{J}_k^2)$. For $a \in \mathbb{Z}(p)$ and $n \in \mathbb{Z} \bmod N_0$, consider the images of the elements D_{an}, where $a \in \mathbb{Z}(p)$ and $n \in \mathbb{Z} \bmod N_0$ (cf. n.1), in $\mathcal{J}_k \bmod (p, \mathcal{J}_k^2)$. Denote these images by same symbols. Then they give a set of free topological generators of the k-module $\mathcal{M}_k$. The action of $\eta \in \mathrm{Aut}K$ on $\mathcal{M}_k$ in terms of these generators is as follows.

Proposition 2.1. 1) $\mathrm{Fr}(t)^*(D_{an}) = D_{a,n-1}$*;*
2) *if* $\eta \in \mathrm{Aut}^0 K$*, then*

$$\sum_{a \in \mathbb{Z}(p)} t^{-a} \eta^*(D_{a0}) \equiv \sum_{a \in \mathbb{Z}(p)} \eta^{-1}(t)^{-a} D_{a0} \bmod (k + (\sigma - \mathrm{id})K) \otimes \mathcal{M}.$$

Proof. 1) Consider the generators $\alpha_r D_a^{(r)}$ of $\mathcal{A}$ from n.1.2, where $a \in \mathbb{Z}(p), 1 \leqslant r \leqslant N_0$. Note that the residue of the corresponding element $e - 1$ modulo $(\sigma - \mathrm{id})K \otimes (\mathcal{J} \bmod \mathcal{J}^2)$ does not depend on the choice of t or of the elements $\alpha_1, \alpha_2, \ldots, \alpha_{N_0}$, because this is the diagonal element of Artin-Schreier duality. Therefore, if $\mathrm{Fr}(t)^*(D_a^{(r)}) = D_a'^{(r)}$ and $\mathrm{Fr}(t)^*(D_0) = D_0'$ then

$$\begin{aligned} e - 1 &\equiv \sigma(\alpha_0) \otimes D_0' + \sum_{a,r} \sigma(\alpha_r) t^{-a} \otimes D_a'^{(r)} \\ &\equiv \alpha_0 \otimes D_0 + \sum_{a,r} \alpha_r t^{-a} \otimes D_a^{(r)} \bmod (\sigma - \mathrm{id})K \otimes (\mathcal{J} \bmod \mathcal{J}^2). \end{aligned} \tag{2.1}$$

So, for any $a \in \mathbb{Z}(p)$, we see that in $k \otimes_{\mathbb{F}_p} \mathcal{M} = \mathcal{M}_k$

$$D_{a0} = \sum_r \alpha_r \otimes D_a^{(r)} = \sum_r \sigma(\alpha_r) \otimes D_a'^{(r)}.$$

Denoting the k-linear extension of $\mathrm{Fr}(t)^*$ by the same symbol, as usual, we have

$$\mathrm{Fr}(t)^*(D_{a0}) = \sum_r \alpha_r \otimes \mathrm{Fr}(t)^*(D_a^{(r)}) = \sum_r \alpha_r \otimes D_a'^{(r)} = \sigma^{-1} D_{a0} = D_{a,-1}.$$

Therefore, for any $a \in \mathbb{Z}(p)$ and $n \in \mathbb{Z} \bmod N_0$, $\mathrm{Fr}(t)^*(D_{an}) = D_{a,n-1}$. Notice also that congruence (2.1) implies that $\mathrm{Fr}(t)^* D_0 = D_0$.

2) Using that η is a k-linear automorphism of K and proceeding similarly to the above part 1) we obtain that

$$\sum_{a\in\mathbb{Z}(p)^0}\eta(t)^{-a}\eta^*(D_{a0})\equiv\sum_{a\in\mathbb{Z}(p)^0}t^{-a}D_{a0}\operatorname{mod}(\sigma-\mathrm{id})K\otimes\mathcal{M}.$$

Now apply $(\eta^{-1}\otimes\mathrm{id})$ to both sides of this congruence and notice that we can omit the terms with index $a=0$ when working modulo $(k+(\sigma-\mathrm{id})K)\otimes\mathcal{M}$, because they belong to $\mathcal{M}_k$. The lemma is proved. $\square$

2.3. If f is a continuous automorphism of the $\mathbb{F}_p$-module $\mathcal{M}$, we agree to use the same notation f for its k-linear extension to an automorphism of $\mathcal{M}_k$. For any $a\in\mathbb{Z}(p)$, set

$$f(D_{a0})=\sum_{\substack{b\in\mathbb{Z}(p)\\ n\in\mathbb{Z}\operatorname{mod}N_0}}\alpha_{abn}(f)D_{bn}.$$

Then all coefficients $\alpha_{abn}(f)$ are in k. Sometimes we shall use the notation $\alpha_{abn}(f)$ if a or b are divisible by p, then it is assumed that $\alpha_{abn}(f)=0$. Notice that for any $m\in\mathbb{Z}\operatorname{mod}N_0$,

$$f(D_{am})=\sum_{\substack{b\in\mathbb{Z}(p)\\ n\in\mathbb{Z}\operatorname{mod}N_0}}\sigma^m(\alpha_{abn}(f))D_{b,n+m}.$$

Definition. For any $v\in\mathbb{N}$, let $\mathcal{M}^{(v)}$ be the minimal closed $\mathbb{F}_p$-submodule in $\mathcal{M}$ such that $\mathcal{M}_k^{(v)}:=\mathcal{M}^{(v)}\otimes k$ is topologically generated over k by all D_{an}, where $a\in\mathbb{Z}(p)$, $a\geqslant v$ and $n\in\mathbb{Z}\operatorname{mod}N_0$. (Notice that $\mathcal{M}=\mathcal{M}^{(1)}$.)

Definition. $\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ is the subset in the group $\mathrm{Aut}\mathcal{M}$, consisting of all continuous $\mathbb{F}_p$-linear automorphisms f satifying $\alpha_{a,b,m\operatorname{mod}N_0}(f)=0$ if $bp^m<a$, for any $a,b\in\mathbb{Z}(p)$ and $-N_0<m\leqslant 0$.

It is easy to see that:

(1) $\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ is a subgroup of $\mathrm{Aut}\mathcal{M}$;

(2) if $f\in\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ then for any $a\in\mathbb{N}$, $f(\mathcal{M}^{(a)})\subset\mathcal{M}^{(a)}$, i.e. f is compatible with the image of the ramification filtration in $\mathcal{M}$;

(3) if $f\in\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ then for any $a\in\mathbb{Z}(p)$, $\alpha_{aa0}\in k^*$ and $\alpha_{aan}(f)=0$ if $n\neq 0$.

Definition. For $f\in\mathrm{Aut}\mathcal{M}$, let $f_{\mathrm{an}}\in\mathrm{End}\,\mathcal{M}$ be such that for all $a\in\mathbb{Z}(p)$,

$$f_{\mathrm{an}}(D_{a0})=\sum_{b\in\mathbb{Z}(p)}\alpha_{ab0}(f)D_{b0}.$$

Proposition 2.2. *If $f, g \in \mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ then for any $a, b \in \mathbb{Z}(p)$ such that $a \leqslant b < ap^{N_0}$,*

$$\alpha_{ab0}(fg) = \sum_c \alpha_{ac0}(f)\alpha_{cb0}(g).$$

Corollary 2.3. *If $v < p^{N_0}$ then the correspondence $f \mapsto f_{\mathrm{an}}$ is a group homomorphism from $\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ to $\mathrm{Aut}_{\mathrm{adm}}\mathcal{M} \,\mathrm{mod}\, \mathcal{M}^{(v)}$.*

Proof. We have $\alpha_{ab0}(fg) =$

$$\sum_{\substack{m+n\equiv 0 \,\mathrm{mod}\, N_0 \\ 0\geqslant n,m>-N_0}} \alpha_{a,c,n \,\mathrm{mod}\, N_0}(f)\sigma^n(\alpha_{c,b,m \,\mathrm{mod}\, N_0}(g))D_{b,(m+n) \,\mathrm{mod}\, N_0}.$$

Then $\alpha_{a,c,n \,\mathrm{mod}\, N_0}(f) \neq 0$ implies that $cp^n \geqslant a$ and $\alpha_{c,b,m \,\mathrm{mod}\, N_0}(g) \neq 0$ implies that $bp^m \geqslant c$. So, if the corresponding coefficient for $D_{b,(m+n) \,\mathrm{mod}\, N_0}$ is not zero then $bp^{m+n} \geqslant a$, i.e. $m+n > -N_0$ and, therefore, $m = n = 0$. □

The following proves that $\mathrm{Aut}^0 K \subset \mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$.

Proposition 2.4. *If $\eta \in \mathrm{Aut}^0 K$ then $\eta^* \in \mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$.*

Proof. For $a \in \mathbb{Z}(p)$, set

$$\eta^{-1}(t)^{-a} \equiv \sum_{\substack{b\in\mathbb{Z}(p) \\ s\geqslant 0}} \gamma_{abs} t^{-bp^s} \,\mathrm{mod}\, k[[t]].$$

Clearly, $\gamma_{abs} = 0$ if $bp^s > a$. It follows from part 2) of proposition 2.1 that

$$\eta^*(D_{b0}) = \sum_{\substack{a\in\mathbb{Z}(p) \\ s\geqslant 0}} \sigma^{-s}(\gamma_{abs})D_{a,-s \,\mathrm{mod}\, N_0}.$$

Therefore, for $0 \leqslant m < N_0$,

$$\alpha_{b,a,-m \,\mathrm{mod}\, N_0}(\eta^*) = \sum_{\substack{s\equiv m \,\mathrm{mod}\, N_0 \\ s\geqslant 0}} \sigma^{-s}(\gamma_{abs})$$

and $a/p^m < b$ implies for $s \equiv m \,\mathrm{mod}\, N_0$, $s \geqslant 0$, that $a/p^s < b$. So, $bp^s > a$, $\gamma_{abs} = 0$ and $\alpha_{b,a,-m \,\mathrm{mod}\, N_0}(\eta^*) = 0$.

The proposition is proved. □

2.4. In this subsection we prove three technical propositions. Notice that in proposition 2.5 we treat the case of fields of characteristic $p \neq 2$ and in proposition 2.6 the characteristic of K is 2. Propositions 2.5-2.7 will be used later in section 5. If $a, b \in \mathbb{N}$ then δ_{ab} is the Kronecker symbol.

Proposition 2.5. *Suppose $p \neq 2$, $w_0 \in \mathbb{N}$, $w_0+1 \leqslant p^{N_0}$ and $f \in \mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ is such that $\alpha_{1a0}(f) = \delta_{1a}$ if $1 \leqslant a < w_0$ and $\alpha_{2a0}(f) = 0$ if $a \equiv 1 \,\mathrm{mod}\, p$ and $a \leqslant w_0$. Then there is an $\eta \in \mathrm{Aut}^0 K$ such that $\eta(t) \equiv t \,\mathrm{mod}\, t^{w_0}$, $\alpha_{1a0}(f\eta^*) = \delta_{1a}$ if $1 \leqslant a < w_0 + 1$, and $\alpha_{2a0}(f\eta^*) = 0$ if $a \equiv 1 \,\mathrm{mod}\, p$ and $a \leqslant w_0 + 1$.*

Proof. Take $\eta\in\mathrm{Aut}^0K$ such that $\eta^{-1}(t)=t(1+\gamma t^{w_0-1})$ with $\gamma\in k$. Then for any $a\in\mathbb{Z}(p)$, $\eta^{-1}(t^{-a})=t^{-a}(1-a\gamma t^{w_0-1})\,\mathrm{mod}\,t^{-a+w_0}$, and part 2) of proposition 2.1 implies that $\alpha_{aa0}(\eta^*)=1$, $\alpha_{ab0}(\eta^*)=0$ if $a<b<a+w_0-1$, $\alpha_{a,a+w_0-1,0}(\eta^*)=-(a+w_0-1)\gamma$.

Therefore, by proposition 2.2 $\alpha_{1a0}(f\eta^*)=\delta_{1a}$ if $1\leqslant a<w_0$ and $\alpha_{2a0}(f\eta^*)=0$ if $a\equiv 1\,\mathrm{mod}\,p$, $a\leqslant w_0$.

Suppose $w_0\not\equiv 0\,\mathrm{mod}\,p$. Then by proposition 2.2

$$\alpha_{1w_00}(f\eta^*)=-w_0\gamma+\alpha_{1w_00}(f)=0$$

if $\gamma=w_0^{-1}\alpha_{1w_00}(f)$. This proves the proposition in the case $w_0\not\equiv 0\,\mathrm{mod}\,p$, because $w_0+1\not\equiv 1\,\mathrm{mod}\,p$ and no conditions are required for $\alpha_{2,w_0+1,0}(f\eta^*)$.

Suppose $w_0\equiv 0\,\mathrm{mod}\,p$. Then there are no conditions for $\alpha_{1w_00}(f\eta^*)$ and by proposition 2.2

$$\begin{aligned}\alpha_{2,w_0+1,0}(f\eta^*)&=\alpha_{220}(f)\alpha_{2,w_0+1,0}(\eta^*)+\alpha_{2,w_0+1,0}(f)\alpha_{w_0+1,w_0+1,0}(\eta^*)\\&=-\alpha_{220}(f)\gamma+\alpha_{2,w_0+1,0}(f)=0\end{aligned}$$

if $\gamma=\alpha_{2,w_0+1,0}(f)\alpha_{220}(f)^{-1}$. (Using that $f\in\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ hence $\alpha_{220}(f)\in k^*$.)

The proposition is proved. □

Proposition 2.6. *Let $M\in\mathbb{N}$, $p=2$, $w_0=4M$ and $w_0+1<2^{N_0}$. Suppose $f\in\mathrm{Aut}_{\mathrm{adm}}\mathcal{M}$ is such that $\alpha_{1a0}(f)=\delta_{1a}$ if $1\leqslant a\leqslant w_0-3$ and $\alpha_{3a0}(f)=\delta_{3a}$ if $3\leqslant a\leqslant w_0-1$. Then there is an $\eta\in\mathrm{Aut}^0K$ such that $\alpha_{1a0}(f\eta^*)=\delta_{1a}$ and $\alpha_{3a0}(f\eta^*)=\delta_{3a}$ if $a\leqslant w_0+1$.*

Proof. 1st step.

Take $\eta_1\in\mathrm{Aut}^0K$ such that $\eta_1^{-1}(t)=t(1+\gamma_1t^{4M-2})$ with $\gamma_1\in k$. Then for $a\in\mathbb{Z}(2)$, $\eta_1^{-1}(t^{-a})\equiv t^{-a}(1+\gamma_1t^{4M-2})\,\mathrm{mod}\,t^{-a+4M}$ and by part 2) of proposition 2.1, $\alpha_{aa0}(\eta_1^*)=1$, $\alpha_{ab0}(\eta_1^*)=0$ if $a<b<a+4M-2$, and $\alpha_{a,a+4M-2,0}(\eta_1^*)=\gamma_1$.

So by proposition 2.2, $\alpha_{1a0}(f\eta_1^*)=\alpha_{1a0}(f)$ if $a\leqslant 4M-3=w_0-3$, $\alpha_{3a0}(f\eta_1^*)=\alpha_{3a0}(f)$ if $a\leqslant 4M-1=w_0-1$, $\alpha_{1,w_0-1,0}(f\eta_1^*)=\alpha_{1,w_0-1,0}(f)+\alpha_{1,w_0-1,0}(\eta_1^*)=0$ if $\gamma_1=\alpha_{1,w_0-1,0}(f)$.

2nd step.

By the above first step we can now assume that $\alpha_{1,w_0-1,0}(f)=0$.

Take $\eta_2\in\mathrm{Aut}^0K$ such that $\eta_2^{-1}(t)=t(1+\gamma_2t^{2M-1})$. Then for $a\in\mathbb{Z}(2)$, $\eta_2^{-1}(t^{-a})\equiv t^{-a}(1+\gamma_2t^{2M-1}+\delta(a)\gamma_2^2t^{4M-2})\,\mathrm{mod}\,t^{-a+4M}$, where $\delta(a)=a(a+1)/2$.

So by part 2) of proposition 2.1, $\alpha_{aa0}(\eta_2^*)=1$, $\alpha_{ab0}(\eta_2^*)=0$ if $a<b<a+4M-2$ (notice that $-a+2M-1\equiv 0\,\mathrm{mod}\,2$), and $\alpha_{a,a+4M-2,0}(\eta_2^*)=\delta(a+4M-2)\gamma_2^2$ (notice that $\delta(a+4M-2)=0$ if $a\equiv 1\,\mathrm{mod}\,4$ and $\delta(a+4M-2)=1$ if $a\equiv 3\,\mathrm{mod}\,4$).

Again by proposition 2.2, $\alpha_{1a0}(f\eta_2^*)=\alpha_{1a0}(f)$ if $a\leqslant 4M-1=w_0-1$ (use that $\alpha_{1,w_0-1,0}(f)=\alpha_{1,w_0-1,0}(\eta_2^*)=0$), $\alpha_{3a0}(f\eta_2^*)=\alpha_{3a0}(f)$ if $a\leqslant 4M-1=w_0-1$, $\alpha_{3,w_0+1,0}(f\eta_2^*)=\alpha_{3,w_0+1,0}(f)+\alpha_{3,w_0+1,0}(\eta_2^*)=0$ if $\gamma_2\in k$ is such that $\gamma_2^2=\alpha_{3,w_0+1,0}(f)$.

3rd step.

Now we can assume that $\alpha_{1,w_0-1,0}(f)=\alpha_{3,w_0+1,0}(f)=0$.

Take $\eta_3\in\mathrm{Aut}^0K$ such that $\eta_3^{-1}(t)=t(1+\gamma_3t^{4M})$. Then for $a\in\mathbb{Z}(2)$, $\eta_3^{-1}(t^{-a})\equiv t^{-a}(1+\gamma_3t^{4M})\bmod t^{-a+4M+2}$, $\alpha_{aa0}(\eta_3^*)=1$, $\alpha_{ab0}(\eta_3^*)=0$ if $a<b<a+4M$, and $\alpha_{a,a+4M,0}(\eta_3^*)=\gamma_3$.

This implies that $\alpha_{1a0}(f\eta_3^*)=\alpha_{1a0}(f)$ if $a\leqslant 4M-1=w_0-1$, $\alpha_{1,w_0+1,0}(f\eta_3^*)=\alpha_{1,w_0+1,0}(f)+\alpha_{1,w_0+1,0}(\eta_3^*)=0$ if $\gamma_3=\alpha_{1,w_0+1,0}(f)$ and $\alpha_{3a0}(f\eta_3^*)=\alpha_{3a0}(f)$ if $a\leqslant w_0+1$.

The proposition is proved. □

Proposition 2.7. *Suppose $a\in\mathbb{Z}(p)$, $w_0\leqslant ap^{N_0}$, where $w_0\in p\mathbb{N}$, $w_0>a+1$ if $p\neq 2$ and $w_0\in 4\mathbb{N}$, $w_0>a+2$ if $p=2$. Suppose $\eta,\eta_1\in\mathrm{Aut}^0K$ are such that for any $b,c\in\mathbb{Z}(p)$ satisfying the restrictions $a\leqslant c\leqslant b<w_0\leqslant ap^{N_0}$, we have the equality*

$$\alpha_{cb0}(\eta^*)=\alpha_{cb0}(\eta_1^*).$$

Then $\eta(t)\equiv\eta_1(t)\bmod t^{v_0}$, where $v_0=w_0-a+1$ if $p\neq 2$ and $v_0=(w_0-a+1)/2$ if $p=2$.

Remark. With notation from Subsection 2.3 this proposition implies that if $\eta_{1\,\mathrm{an}}^*\equiv\eta_{\mathrm{an}}^*\bmod\mathcal{M}^{(w_0)}$ then $\eta(t)\equiv\eta_1(t)\bmod t^{v_0}$.

Proof. Use proposition 2.2 to reduce the proof to the case $\eta_1(t)=t$.

Suppose, first, that $\eta^{-1}(t)=\alpha t\bmod t^2$. Then

$$\alpha_{cc0}(\eta^*)=\alpha^{-c}=1. \tag{2.2}$$

If $a+1\in\mathbb{Z}(p)$ then $p\neq 2$ and we can use formula (2.2) for $c=a,a+1$ to prove that $\alpha=1$. Suppose $a+1\notin\mathbb{Z}(p)$. If $p=2$ use (2.2) for $c=a,a+2<w_0$, and if $p\neq 2$ use (2.2) for $c=a+2,a+3<w_0$ to prove again that $\alpha=1$.

Assume now that $p\neq 2$.

Suppose $\eta^{-1}(t)\equiv t+\alpha t^{v-1}\bmod t^v$ with $v\geqslant 3$ and $\alpha\in k^*$. If $a+v-2\in\mathbb{Z}(p)$ then by part 2) of proposition 2.1 $\alpha_{a,a+v-2,0}(\eta^*)\neq 0$. This implies that $a+v-2\geqslant w_0+1$, i.e. $v\geqslant w_0-a+1$, as required. If $a+v-2\equiv 0\bmod p$ then by part 2) of proposition 2.1 $\alpha_{a+1,a+v-1,0}(\eta^*)\neq 0$.This implies that $a+v-1\geqslant w_0+1$ and $v\geqslant w_0-a+2>w_0-a+1$. The case $p\neq 2$ is considered.

Assume now that $p=2$.

Suppose that $M\in\mathbb{N}$ is such that

$$\eta^{-1}(t)=t\left(1+\sum_{r\geqslant 2M-1}\gamma_rt^r\right)\equiv t\,\mathrm{mod}\,t^{2M}$$

with either $\gamma_{2M-1}\neq 0$ or $\gamma_{2M}\neq 0$.

Therefore, if $r\equiv 0\,\mathrm{mod}\,2$, $r\geqslant 2M-1$ and $a+r<ap^{N_0}$ then by part 2) of proposition 2.1 $\alpha_{a,a+r,0}(\eta^*)=\gamma_r$. This implies that either $2M\geqslant w_0$ (and the proposition is proved) or $2M\leqslant w_0-2$, $\gamma_{2M}=0$ and $\gamma_{2M-1}\neq 0$.

Suppose $a+4M<w_0$. Then with the notation from the second step in the proof of proposition 2.6, we have

$$\alpha_{a,a+4M-2,0}(\eta^*)=\gamma_{4M-2}+\gamma_{2M-1}^2\delta(a+4M-2)$$
$$\alpha_{a+2,a+4M,0}(\eta^*)=\gamma_{4M-2}+\gamma_{2M-1}^2\delta(a+4M).$$

The sum of the right hand sides of the above two equalities is $\gamma_{2M-1}^2\neq 0$, because $\delta(a+4M-2)+\delta(a+4M)=1$. Therefore, at least one of their left hand sides is not zero. This means that the assumption about $a+4M<w_0$ was wrong. Therefore, $4M>w_0-a$ and $2M\geqslant(w_0-a+1)/2$.

The proposition is proved. □

3. Compatible systems of group morphisms

For any $s\in\mathbb{Z}_{\geqslant 0}$, let K_s be the unramified extension of K in $K(p)$ of degree p^s. Then $K_s=k_s((t))$, where $t=t_K$ is a fixed uniformiser, $k\subset k_s$, $[k_s:k]=p^s$, $k_s\simeq\mathbb{F}_{q_s}$, $q_s=p^{N_s}$ with $N_s=N_0p^s$.

Let K_{ur} be the union of all K_s, $s\geqslant 0$. This is the maximal unramified extension of K in $K(p)$ and its residue field coincides with the residue field $k(p)$ of $K(p)$. Let $I_{K_{\mathrm{ur}}}(p)^{\mathrm{ab}}$, resp. $I_{K_s}(p)^{\mathrm{ab}}$, for $s\in\mathbb{Z}_{\geqslant 0}$, be the images of the inertia subgroups of $\mathrm{Gal}(K(p)/K_{\mathrm{ur}})$, resp. $\mathrm{Gal}(K(p)/K_s)$, in the corresponding maximal abelian quotients. Then $I_{K_{\mathrm{ur}}}(p)^{\mathrm{ab}}=\varprojlim_s I_{K_s}(p)^{\mathrm{ab}}$.

3.1. For $s\geqslant 0$, introduce the $\mathbb{F}_p$-modules $\mathcal{M}_{Ks}=I_{K_s}(p)^{\mathrm{ab}}\otimes\mathbb{F}_p$ and $\mathcal{M}_{K\mathrm{ur}}=I_{K_{\mathrm{ur}}}(p)^{\mathrm{ab}}\otimes\mathbb{F}_p$ with the corresponding $k(p)$-modules $\bar{\mathcal{M}}_{Ks}=\mathcal{M}_{Ks}\hat{\otimes}_{\mathbb{F}_p}k(p)$ and $\bar{\mathcal{M}}_{K\mathrm{ur}}=\mathcal{M}_{K\mathrm{ur}}\hat{\otimes}_{\mathbb{F}_p}k(p)$. Then for all $s\geqslant 0$, we have natural connecting morphisms $j_s:\mathcal{M}_{K,s+1}\longrightarrow\mathcal{M}_{Ks}$ and $\bar{j}_s:\bar{\mathcal{M}}_{K,s+1}\longrightarrow\bar{\mathcal{M}}_{Ks}$ (both are induced by the natural group embeddings $\Gamma_{K_{s+1}}\longrightarrow\Gamma_{K_s}$). Therefore, we have projective systems $\{\mathcal{M}_{Ks},j_s\}$ and $\{\bar{\mathcal{M}}_{Ks},\bar{j}_s\}$ and natural identifications $\mathcal{M}_{K\mathrm{ur}}=\varprojlim_s\mathcal{M}_{Ks}$ and $\bar{\mathcal{M}}_{K_{\mathrm{ur}}}=\varprojlim_s\bar{\mathcal{M}}_{K_s}$.

Let $\mathcal{M}_{K\infty}$ be the $k(p)$-submodule in $\bar{\mathcal{M}}_{K\mathrm{ur}}$ which is topologically generated by all $D_{an}^{\infty}:=\varprojlim_s D_{a,n\,\mathrm{mod}\,N_s}^{(s)}$, where $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}$. Here for

$a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\,\mathrm{mod}\,N_s$, $D^{(s)}_{an}$ are generators for $\bar{\mathcal{M}}_{Ks}$, which are analogues of the generators D_{an} introduced in Section 2 for the k-module $\mathcal{M}_k$. Notice that the generators $D^{(s)}_{an}$ depend on the choice of the uniformising element t in K.

Proposition 3.1. *The $k(p)$-submodule $\mathcal{M}_{K\infty}$ of $\bar{\mathcal{M}}_{K\mathrm{ur}}$ does not depend on the choice of t.*

Proof. Let t_1 be another uniformiser in K. Introduce $\eta\in\mathrm{Aut}^0(K_{\mathrm{ur}})$ such that $\eta(t)=t_1$. The proposition will be proved if we show that $\eta^*(\mathcal{M}_{K\infty})=\mathcal{M}_{K\infty}$.

For $s\geqslant 0$, let $\eta_s=\eta|_{K_s}\in\mathrm{Aut}^0K_s$. Then for $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\,\mathrm{mod}\,N_s$,

$$\eta_s^*(D^{(s)}_{an})=\sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z}\,\mathrm{mod}\,N_s}}\sigma^n\alpha_{abm}(\eta_s^*)D^{(s)}_{b,m+n},$$

where the coefficients $\alpha_{abm}(\eta_s^*)\in k_s$ satisfy the following compatibility conditions (using that $j_s(D^{(s)}_{an})=D^{(s-1)}_{a,n\,\mathrm{mod}\,N_{s-1}}$):

if $a,b\in\mathbb{Z}(p)$ and $m\in\mathbb{Z}\,\mathrm{mod}\,N_{s-1}$ then

$$\sum_{n\,\mathrm{mod}\,N_{s-1}=m}\alpha_{abn}(\eta_s^*)=\alpha_{abm}(\eta_{s-1}^*).$$

By proposition 2.4, if $0\leqslant m<N_s$ and $b/p^m<a$ then $\alpha_{a,b,-m\,\mathrm{mod}\,N_s}(\eta_s^*)=0$. Therefore, if s is such that $b/p^{N_s}<a$ then $\alpha^\infty_{a,b,-m}(\eta^*):=\alpha_{a,b,-m\,\mathrm{mod}\,N_s}(\eta_s^*)$ does not depend on s and for any $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}_{\geqslant 0}$,

$$\eta^*(D^\infty_{an})=\sum_{b\in\mathbb{Z}(p),m\geqslant 0}\sigma^n\alpha^\infty_{a,b,-m}(\eta^*)D^\infty_{b,n-m}\in\mathcal{M}_{K\infty}.$$

The proposition is proved. □

3.2. Consider the identification of class field theory $I_{K_s}(p)^{\mathrm{ab}}=U_{K_s}$, where U_{K_s} is the group of principal units of K_s. Define the continuous morphism of topological $k(p)$-modules

$$\pi_{Ks}:\bar{\mathcal{M}}_{Ks}=I_{K_s}(p)^{\mathrm{ab}}\hat{\otimes}k(p)\longrightarrow\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}},$$

by $\pi_{Ks}(u\otimes\alpha)=\alpha\,\mathrm{d}(u)/u$ for $u\in U_{K_s}$ and $\alpha\in k(p)$. Here $\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$ is the completion of the module of differentials of the valuation ring $O_{K_{\mathrm{ur}}}$ with respect to the t-adic topology. Notice that for any $a\in\mathbb{Z}(p)$ and $0\leqslant n<N_s$,

$$D^{(s)}_{a,n\,\mathrm{mod}\,N_s}=\sum_{0\leqslant i<N_s}u_i\otimes(\sigma^n\alpha_i\,\mathrm{mod}\,p).$$

Here $\{\alpha_i \mid 1 \leqslant i \leqslant N_s\}$ is a $\mathbb{Z}_p$-basis of $W(k_s)$. If $\{\beta_i \mid 1 \leqslant i \leqslant N_s\}$ is its dual basis then for $1 \leqslant i \leqslant N_s$, $u_i = E(\beta_i, t^a)^{1/a}$, cf. Subsection 1.4. Therefore,

$$\pi_{Ks}(D^{(s)}_{a,n \bmod N_s}) = \left(\sum_{i\geqslant 0} t^{ap^{n+iN_s}}\right)\frac{\mathrm{d}(t)}{t}.$$

It is easy to see that $\pi_{K\mathrm{ur}} := \varprojlim \pi_{Ks}$ is a continuous map from $\bar{\mathcal{M}}_{K\mathrm{ur}}$ to $\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$.

Notice that if $\bar{n} = \varprojlim (n_s \bmod N_s) \in \varprojlim_s \mathbb{Z}/N_s\mathbb{Z}$, where all $n_s \in [0, N_s)$ and if $D^{\infty}_{a\bar{n}} = \varprojlim_s D^{(s)}_{a,n_s \bmod N_s}$, for $a \in \mathbb{Z}(p)$, then $\pi_{K\mathrm{ur}}(D^{\infty}_{a\bar{n}}) = 0$ if $\bar{n} \notin \mathbb{Z}_{\geqslant 0} \subset \varprojlim \mathbb{Z}/N_s\mathbb{Z}$, and $\pi_{K\mathrm{ur}}(D^{\infty}_{an}) = t^{ap^n-1}\,\mathrm{d}(t)$ if $\bar{n} = n \in \mathbb{Z}_{\geqslant 0}$.

Let $\pi_{K\infty} := \pi_{K\mathrm{ur}}|_{\mathcal{M}_{K\infty}}$. Then one can easily prove the following proposition.

Proposition 3.2. 1) $\pi_{K\infty} : \mathcal{M}_{K\infty} \longrightarrow \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$ *is a continuous epimorphism of $k(p)$-modules;*
2) $\ker \pi_{K\infty}$ *is the $k(p)$-submodule in $\mathcal{M}_{K\infty}$ topologically generated by all D^{∞}_{an} with $n < 0$.*

3.3. Admissible systems of group morphisms. Suppose $K' = k((t')) \subset K(p)$ has the same residue field as K. Using K' instead of K we can introduce analogues $\mathcal{M}_{K's}$, $\bar{\mathcal{M}}_{K's}$, $\mathcal{M}_{K'\infty}$, etc. of $\mathcal{M}_{Ks}$, $\bar{\mathcal{M}}_{Ks}$, $\mathcal{M}_{K\infty}$, etc.

Definition. $f_{KK'} = \{f_{KK's}\}_{s\geqslant 0}$ is a family of continuous morphisms of $\mathbb{F}_p$-modules $f_{KK's} : \mathcal{M}_{Ks} \longrightarrow \mathcal{M}_{K's}$ which are always assumed to be compatible, i.e. for all $s \geqslant 0$, $f_{KK',s+1}j'_s = j_s f_{KK's}$. Here $j_s : \mathcal{M}_{K,s+1} \longrightarrow \mathcal{M}_{Ks}$ and $j'_s : \mathcal{M}_{K',s+1} \longrightarrow \mathcal{M}_{K's}$ are connecting morphisms.

We shall denote the $k(p)$-linear extension of $f_{KK's}$ by the same symbol $f_{KK's}$. Set

$$f_{KK'\mathrm{ur}} := \varprojlim_s f_{KK's} : \bar{\mathcal{M}}_{K\mathrm{ur}} \longrightarrow \bar{\mathcal{M}}_{K'\mathrm{ur}}.$$

Definition. With the above notation $f_{KK'}$ is called admissible if:
A1. There is a continuous $k(p)$-linear isomorphism $f_{KK'\infty} : \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}} \longrightarrow \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$ such that $f_{KK'\mathrm{ur}}\pi_{K'\mathrm{ur}} = \pi_{K\mathrm{ur}} f_{KK'\infty}$;
A2. $f_{KK'\infty}$ commutes with the Cartier operators C and C' on $\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$ and, resp., $\hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$;
A3. For all $m \in \mathbb{N}$, $f_{KK'\infty}\left(t^m \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}\right) \subset t'^m \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$.

Remark. Recall that the Cartier operator $C:\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}\longrightarrow\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$ is uniquely determined by the following properties:
a) $C(\mathrm{d}(\hat{O}_{K_{\mathrm{ur}}}))=0$;
b) if $f\in t\hat{O}_{K_{\mathrm{ur}}}$ then $C(f^p\,\mathrm{d}(t)/t)=f\,\mathrm{d}(t)/t$.
It can be shown that the definition of C does not depend on the choice of the uniformiser t, C is σ^{-1}-linear and $\mathrm{Ker}C=\mathrm{d}(\hat{O}_{K_{\mathrm{ur}}})$.

The following properties of admissible systems $f_{KK'}=\{f_{KK's}\}_{s\geqslant 0}$ follow directly from the above definition:

(1) the map $f_{KK'\infty}$ is uniquely determined by $f_{KK'\mathrm{ur}}$;

(2) if $K''=k((t''))\subset K(p)$ and $g_{K'K''}=\{g_{K'K''s}\}_{s\geqslant 0}$ is admissible then so is the composition $(fg)_{KK''}:=\{f_{KK's}g_{K'K''s}\}_{s\geqslant 0}$ and it holds $(fg)_{KK''\infty}=f_{KK'\infty}g_{K'K''\infty}$;

(3) $f_{KK'\infty}(\mathrm{d}\,\hat{O}_{K_{\mathrm{ur}}})\subset\mathrm{d}\,\hat{O}_{K'_{\mathrm{ur}}}$;

(4) for all $a,b\in\mathbb{Z}(p)$ and $m\in\mathbb{Z}_{\geqslant 0}$, there are unique $\alpha^{\infty}_{a,b,-m}(f_{KK'})\in k(p)$ such that if $n\geqslant 0$ then

$$f_{KK'\infty}\left(t^{ap^n}\frac{\mathrm{d}(t)}{t}\right)=\sum_{\substack{b\in\mathbb{Z}(p)\\0\leqslant m\leqslant n}}\sigma^n\alpha^{\infty}_{a,b,-m}(f_{KK'})t'^{bp^{n-m}}\frac{\mathrm{d}(t')}{t'};\tag{3.1}$$

(5) the above coefficients $\alpha^{\infty}_{a,b,-m}(f_{KK'})$ satisfy the following property: if $b/p^m<a$ then $\alpha^{\infty}_{a,b,-m}(f_{KK'})=0$.

Definition. With the above notation an admissible compatible system $f_{KK'}$ will be called special admissible if $f_{KK'\mathrm{ur}}(\mathcal{M}_{K\infty})\subset\mathcal{M}_{K'\infty}$.

Notice that the composition of special admissible systems is again special admissible.

3.4. Characterisation of special admissible systems. Let $f_{KK'}=\{f_{KK's}\}_{s\geqslant 0}$ be a compatible system. Then for any $s\geqslant 0$, the $k(p)$-linear morphism $f_{KK's}:\bar{\mathcal{M}}_{Ks}\longrightarrow\bar{\mathcal{M}}_{K's}$ is defined over $\mathbb{F}_p$, i.e. it comes from a $\mathbb{F}_p$-linear morphism $f_{KK's}:\mathcal{M}_{Ks}\longrightarrow\mathcal{M}_{K's}$. Therefore, in terms of the standard generators $D^{(s)}_{an}$ and $D'^{(s)}_{an}$ (which correspond to the uniformisers $t=t_K$ and, resp., $t'=t_{K'}$), we have for any $s\geqslant 0$ and $a\in\mathbb{Z}(p)$ that

$$f_{KK's}(D^{(s)}_{a0})=\sum_{\substack{b\in\mathbb{Z}(p)\\m\in\mathbb{Z}\,\mathrm{mod}\,N_s}}\alpha_{abm}(f_{KK's})D'^{(s)}_{bm},$$

where all $\alpha_{abm}(f_{KK's}) \in k_s \subset k(p)$. Notice that for all $n \in \mathbb{Z} \bmod N_s$, it holds

$$f_{KK's}(D_{an}^{(s)}) = \sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z} \bmod N_s}} \sigma^n \alpha_{abm}(f_{KK's}) D'^{(s)}_{b,m+n}.$$

Proposition 3.3. *Suppose* $f_{KK'} = \{f_{KK's}\}_{s\geqslant 0}$ *is a compatible system. Then it is special admissible if and only if for any* $s \geqslant 0$*, there are* $v_s \in \mathbb{N}$ *such that* $v_s \to \infty$ *if* $s \to \infty$*, and if* $a, b < v_s$*,* $m \geqslant 0$ *and* $b/p^m < a$ *then* $\alpha_{a,b,-m \bmod N_s}(f_{KK's}) = 0$.

Proof. Suppose $f_{KK'}$ is special admissible. Then $f_{KK'\mathrm{ur}}(\mathcal{M}_{K\infty}) \subset \mathcal{M}_{K'\infty}$ and for all $a \in \mathbb{Z}(p)$ and $n \in \mathbb{Z}$,

$$f_{KK'\mathrm{ur}}(D_{an}^{\infty}) = \sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z}}} \beta_{anbm} D'^{\infty}_{b,n+m}.$$

Here all coefficients $\beta_{anbm} \in k(p)$ and because $f_{KK'\mathrm{ur}}$ commutes with σ, there are $\gamma_{abm} \in k(p)$ such that $\beta_{anbm} = \sigma^n(\gamma_{abm})$. Therefore, if $a, b \in \mathbb{Z}(p)$, $m \in \mathbb{Z}$ and $\gamma_{abm} \neq 0$ then $m \leqslant 0$ and $\alpha^{\infty}_{abm}(f_{KK'}) = \gamma_{abm}$.

If $s \geqslant 0$, $a \in \mathbb{Z}(p)$,

$$f_{KK's}(D_{a0}^{(s)}) = \sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z} \bmod N_s}} \alpha_{a,b,-m}(f_{KK's}) D'^{(s)}_{b,-m}$$

and $b/p^{N_s} < a$ then for any $m \geqslant 0$, $\alpha_{a,b,-m \bmod N_s}(f_{KK's}) = \alpha^{\infty}_{a,b,-m}(f_{KK'})$. This implies that $\alpha_{a,b,-m \bmod N_s}(f_{KK's}) = 0$ if $a, b < p^{N_s}$ and $b/p^m < a$. Therefore, we can take $v_s = p^{N_s}$. This proves the "only if " part of the proposition.

Suppose now that $v_s \to \infty$ if $s \to \infty$ and for $a, b \in \mathbb{Z}(p)$, $m \geqslant 0$,

$$\alpha_{a,b,-m \bmod N_s}(f_{KK's}) = 0$$

if $a, b < v_s$ and $b/p^m < a$. If in addition $p^{N_s} > b$ then $\alpha_{a,b,-m \bmod N_s}(f_{KK's})$ does not depend on s and can be denoted by $\alpha^{\infty}_{a,b,-m}$. Clearly, $\alpha^{\infty}_{a,b,-m} = 0$ if $b/p^m < a$. Let $a \in \mathbb{Z}(p)$ and

$$d = f_{KK'\mathrm{ur}}(D_{a0}^{\infty}) - \sum_{\substack{b\in\mathbb{Z}(p)\\ m\geqslant 0}} \alpha^{\infty}_{a,b,-m} D'^{\infty}_{b,-m}.$$

Let $s \geqslant 0$ and let $d_s \in \bar{\mathcal{M}}_{Ks}$ be the image of d under the natural projection $\bar{\mathcal{M}}_{K\mathrm{ur}} \longrightarrow \bar{\mathcal{M}}_{Ks}$. If $s_1 \geqslant s$ then the corresponding projection $d_{s_1} \in \bar{\mathcal{M}}_{Ks_1}$ is a linear combination of $D^{(s_1)}_{bm}$ with $b > p^{N_{s_1}}$. Therefore, d_s also does not contain the terms $D^{(s)}_{bm}$ for which $b > p^{N_{s_1}}$. Because $\lim_{s_1\to\infty} N_{s_1} = \infty$, this implies that $d_s = 0$ for all $s \geqslant 0$ and, therefore, $d = 0$. So, $f_{KK'\mathrm{ur}}(\mathcal{M}_{K\infty}) \subset \mathcal{M}_{K'\infty}$.

Set $\alpha^{\infty}_{a,b,-m}(f_{KK'}) := \alpha^{\infty}_{a,b,-m}$ and define $f_{KK'\infty} : \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}} \longrightarrow \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$ by formula (3.1). It is easy to see that $f_{KK'\infty}$ satisfies the requirements **A1-A3** from the definition of admissible system in Subsection 3.3. This proves the "if" part of our proposition.

□

Remark. Any special admissible $f_{KK'}$ can be defined as a $k(p)$-linear isomorphism $f_{KK'\mathrm{ur}} : \mathcal{M}_{K\infty} \longrightarrow \mathcal{M}_{K'\infty}$ such that

(1) $f_{KK'\mathrm{ur}}$ commutes with σ;

(2) if $a \in \mathbb{Z}(p)$ then

$$f_{KK'\mathrm{ur}}(D^{\infty}_{a0}) = \sum_{\substack{b \in \mathbb{Z}(p) \\ m \geqslant 0}} \alpha_{a,b,-m} D'^{\infty}_{b,-m}$$

where $\alpha_{a,b,-m} = 0$ if $b/p^m < a$.

3.5. Analytic compatible systems. Suppose $K, K' \subset K(p)$. Then the corresponding residue fields k and k' are subfields of the residue field $k(p) \subset \bar{\mathbb{F}}_{q_0}$. Therefore, if $K \simeq K'$ then $k = k'$ and we can introduce the set $\mathrm{Iso}^0(K, K')$ of field isomorphisms $\eta : K \longrightarrow K'$ such that $\eta|_k = \mathrm{id}$. Notice that any $\eta \in \mathrm{Iso}^0(K, K')$ induces a $k(p)$-linear map $\Omega^1(\eta) : \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}} \longrightarrow \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$.

For all $s \geqslant 0$, any $\eta \in \mathrm{Iso}^0(K, K')$ can be naturally extended to $\eta_s \in \mathrm{Iso}^0(K_s, K'_s)$. Then $\eta^*_{KK'} = \{\eta^*_s\}_{s \geqslant 0}$ is a compatible system and $\eta_{KK'\infty} = \Omega^1(\eta)$. Propositions 2.4 and 3.3 imply that $\eta^*_{KK'}$ is a special admissible system.

Consider the opposite situation. Choose a uniformiser t_K in K and introduce $\mathrm{Fr}(t_K) \in \mathrm{Aut}(K_{\mathrm{ur}})$ such that $\mathrm{Fr}(t_K) : t_K \mapsto t_K$ and $\mathrm{Fr}(t_K)|_{k(p)} = \sigma$. Then for all $s \geqslant 0$, $\mathrm{Fr}(t_K)$ induces an automorphism of K_s which will be denoted by $\mathrm{Fr}(t_K)_s$. Then $\mathrm{Fr}(t_K)^* = \{\mathrm{Fr}(t_K)_s\}_{s \geqslant 0}$ is a compatible system, but this system is not admissible: the corresponding map $\mathrm{Fr}(t_K)_\infty$ coincides with the Cartier operator and, therefore, is not $k(p)$-linear.

More generally, consider a compatible system $\theta_{KK'} = \{\theta_{KK's}\}_{s \geqslant 0}$ where for all $s \geqslant 0$, $\theta_{KK's} = \theta^*_s$ and $\theta_s \in \mathrm{Iso}(K_s, K'_s)$. Then after choosing a uniformising element $t_{K'}$ in K' we have $\theta_s = \eta_s \mathrm{Fr}(t_{K'})^{n_s}$, for all $s \geqslant 0$, where $\eta_s \in \mathrm{Iso}^0(K_s, K'_s)$ and $n_{s+1} \equiv n_s \bmod N_s$. If $\bar{n} = \varprojlim_s n_s \in \varprojlim_s \mathbb{Z}/N_s\mathbb{Z}$ then $\theta_{KK'}$ is the composite of the special admissible system $\{\eta^*_s\}_{s \geqslant 0}$ and the system $\mathrm{Fr}(t_{K'})^{\bar{n}*}$ which is special admissible if and only if $\bar{n} = 0$. Therefore, $\theta_{KK'}$ is special admissible if and only if it comes from a compatible system of field isomorphisms $\eta_s \in \mathrm{Iso}^0(K_s, K'_s)$.

3.6. Locally analytic systems.

Definition. If $f_{KK'}$ is an admissible system, then $f_{KK'\mathrm{an}} := f_{KK'\infty}|_{\mathrm{d}(\hat{O}_{K_{\mathrm{ur}}})}$.

Remark. Notice the following similarity to the definition of f_{an} for $f \in \mathrm{Aut}\mathcal{M}$ from n.2.3. If $f_{KK} = \{f_{KKs}\}_{s\geqslant 0}$ is any admissible system then $g_{KK} := \{f_{KKs\mathrm{an}}\}_{s\geqslant 0}$ is also admissible and $f_{KK\mathrm{an}} = g_{KK\mathrm{an}}$.

Definition. An admissible system $f_{KK'} = \{f_{KK's}\}_{s\geqslant 0}$ will be called locally analytic if for any $s \geqslant 0$, there are $v_s \in \mathbb{N}$ and $\eta_s \in \mathrm{Iso}^0(K, K')$ such that $v_s \to +\infty$ as $s \to \infty$ and $f_{KK'\mathrm{an}} \equiv \mathrm{d}(\eta_s)\hat{\otimes}_k k(p) \bmod t'^{v_s}$.

Proposition 3.4. *Suppose that $f_{KK'} = \{f_{KK's}\}_{s\geqslant 0}$ is special admissible and locally analytic. Then there is an $\eta \in \mathrm{Iso}^0(K, K')$ such that $f_{KK'\mathrm{an}} = \mathrm{d}(\eta)\hat{\otimes}_k k(p)$.*

Proof. If $s \geqslant 0$ and $a, b \in \mathbb{Z}(p)$ are such that $v_s/p^{N_0} < a, b < v_s$, then

$$\alpha^{\infty}_{ab0}(f_{KK'}) = \alpha_{ab0}(\eta_s^*) = \alpha_{ab0}(f_{KK's}) = \alpha_{ab0}(f_{KK'0}) \in k.$$

Therefore, by Proposition 2.7, all conjugates of η_s over K are congruent modulo $t'^{v_s(1-p^{-N_0})/\delta_p}$, and $\eta_s(t) \in k[[t']] \bmod t'^{v_s(1-p^{-N_s})/\delta_p}$, where δ_p is 1 if $p \neq 2$ and $\delta_p = 2$ if $p = 2$. This implies that $\alpha_{ab0}(f_{KK's}) \in k$ if $a, b < v_s(1-p^{-N_s})/\delta_p$.

If $b < p^{N_s}$ then $\alpha_{ab0}(f_{KK's}) = \alpha^{\infty}_{ab0}(f_{KK'})$. So, $\alpha^{\infty}_{ab0}(f_{KK'}) \in k$ if $b < c_s := \min\left\{p^{N_s}, v_s(1-p^{-N_s})/\delta_p\right\}$. But $c_s \to \infty$ if $s \to \infty$ and, therefore, $\alpha^{\infty}_{ab0}(f_{KK'}) \in k$ for all $a, b \in \mathbb{Z}(p)$.

As we have already noticed, if $b < \min\{p^{N_s}, v_s\}$ then

$$\alpha_{ab0}(f_{KK's}) = \alpha_{ab0}(\eta_s^*) = \alpha^{\infty}_{ab0}(f_{KK'}).$$

Therefore, by Proposition 2.7 there exists $\varprojlim_s \eta_s := \eta \in \mathrm{Iso}^0(K, K')$ and $f_{KK'\mathrm{an}} = \mathrm{d}(\eta)\hat{\otimes}_k k(p)$.

The proposition is proved. □

3.7. Comparability of admissible systems. With the above notation suppose L, L' are finite field extensions of K, resp. K', in $K(p)$. Let $g_{LL'} = \{g_{LL's}\}_{s\geqslant 0}$ be a compatible family of continuous field isomorphisms $g_{LL's} : L_s \longrightarrow L'_s$. Then the natural embeddings $\Gamma_L(p) \subset \Gamma_K(p)$ and $\Gamma_{L'}(p) \subset \Gamma_{K'}(p)$ induce embeddings $\Gamma_{L_s}(p) \subset \Gamma_{K_s}(p)$ and $\Gamma_{L'_s}(p) \subset \Gamma_{K'_s}(p)$, for any $s \geqslant 0$.

Definition. With the above assumptions the systems $g_{LL'}$ and $f_{KK'}$ will be called comparable if, for all $s \geqslant 0$, there is the following commutative diagram

$$\begin{array}{ccc} \mathcal{M}_{Ls} & \xrightarrow{g_{LL's}} & \mathcal{M}_{L's} \\ \big\downarrow j_s & & \big\downarrow j'_s \\ \mathcal{M}_{Ks} & \xrightarrow{f_{KK's}} & \mathcal{M}_{K's} \end{array}$$

where the vertical arrows j_s and j'_s are induced by the embeddings $\Gamma_{L_s}(p) \subset \Gamma_{K_s}(p)$ and, resp., $\Gamma_{L'_s}(p) \subset \Gamma_{K'_s}(p)$.

If $g_{LL'}$ and $f_{KK'}$ are comparable then we have the following commutative diagram

$$\begin{array}{ccc} \bar{\mathcal{M}}_{L\mathrm{ur}} & \xrightarrow{g_{LL'\mathrm{ur}}} & \bar{\mathcal{M}}_{L'\mathrm{ur}} \\ \big\downarrow j_{\mathrm{ur}} & & \big\downarrow j'_{\mathrm{ur}} \\ \bar{\mathcal{M}}_{K\mathrm{ur}} & \xrightarrow{f_{KK'\mathrm{ur}}} & \bar{\mathcal{M}}_{K'\mathrm{ur}} \end{array} \tag{3.2}$$

where $j_{\mathrm{ur}} := \varprojlim_s j_s \hat{\otimes}_{k_s} k(p)$ and $j'_{\mathrm{ur}} := \varprojlim_s j'_s \hat{\otimes}_{k_s} k(p)$. Notice that j_{ur} and j'_{ur} are epimorphic. Indeed, let U_{L_s}, U_{K_s} be principal units in L_s, resp. K_s. Then $\mathcal{M}_{L\mathrm{ur}} = \varprojlim_s U_{L_s}/U_{L_s}^p$ and $\mathcal{M}_{K\mathrm{ur}} = \varprojlim_s U_{K_s}/U_{K_s}^p$ contain as dense subsets the images of the groups of principal units $U_{L_{\mathrm{ur}}}$, resp. $U_{K_{\mathrm{ur}}}$, of the fields L_{ur}, resp. K_{ur}. By class field theory, j_{ur} is induced by the norm map $N = N_{L_{\mathrm{ur}}/K_{\mathrm{ur}}}$ from L^*_{ur} to K^*_{ur}. By [6], Ch 2, $N(U_{L_{\mathrm{ur}}})$ is dense in $U_{K_{\mathrm{ur}}}$ and, therefore, j_{ur} (together with j'_{ur}) is surjective.

Suppose L/K and L'/K' are Galois extensions. Denote their inertia subgroups by $I_{L/K}$ and $I_{L'/K'}$. Then we have identifications $I_{L/K} = \mathrm{Gal}(L_{\mathrm{ur}}/K_{\mathrm{ur}})$ and $I_{L'/K'} = \mathrm{Gal}(L'_{\mathrm{ur}}/K'_{\mathrm{ur}})$.

Consider the following condition:

C. *There is a group isomorphism $\kappa : I_{L/K} \longrightarrow I_{L'/K'}$ such that for any $\tau \in I_{L/K}$, $\tau^*_{LL\mathrm{ur}} g_{LL'\mathrm{ur}} = g_{LL'\mathrm{ur}} \kappa(\tau)^*_{L'L'\mathrm{ur}}$.*

Proposition 3.5. *Suppose $g_{LL'}$ and $f_{KK'}$ are comparable and $g_{LL'}$ satisfies the above condition* **C**. *If $g_{LL'}$ is admissible then $f_{KK'}$ is also admissible.*

Proof. Because $g_{LL'}$ is admissible we have the following commutative diagram

$$\begin{array}{ccc} \bar{\mathcal{M}}_{L\mathrm{ur}} & \xrightarrow{g_{LL'\mathrm{ur}}} & \bar{\mathcal{M}}_{L'\mathrm{ur}} \\ \Big\downarrow \pi_{L\mathrm{ur}} & & \Big\downarrow \pi_{L'\mathrm{ur}} \\ \hat{\Omega}^1_{O_{L_{\mathrm{ur}}}} & \xrightarrow{g_{LL'\infty}} & \hat{\Omega}^1_{O_{L'_{\mathrm{ur}}}} \end{array} \tag{3.3}$$

If $\tau \in I_{L/K} \subset \mathrm{Aut}^0(L_{\mathrm{ur}})$ then it follows from the definition of $\pi_{L_{\mathrm{ur}}}$ that

$$\tau^* \pi_{L\mathrm{ur}} = \pi_{L\mathrm{ur}} \Omega(\tau). \tag{3.4}$$

This means that $\pi_{L\mathrm{ur}}$ transforms the natural action of $I_{L/K}$ on $\bar{\mathcal{M}}_{L\mathrm{ur}}$ into the natural action of $I_{L/K}$ on $\hat{\Omega}^1_{O_{L_{\mathrm{ur}}}}$. Because j_{ur} is induced by the norm map of the field extension $L_{\mathrm{ur}}/K_{\mathrm{ur}}$, this gives us the following commutative diagram

$$\begin{array}{ccc} \bar{\mathcal{M}}_{L\mathrm{ur}} & \xrightarrow{\pi_{L\mathrm{ur}}} & \hat{\Omega}^1_{O_{L_{\mathrm{ur}}}} \\ \Big\downarrow j_{\mathrm{ur}} & & \Big\downarrow \mathrm{Tr} \\ \bar{\mathcal{M}}_{K\mathrm{ur}} & \xrightarrow{\pi_{K\mathrm{ur}}} & \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}} \end{array} \tag{3.5}$$

where Tr is induced by the trace of the extension $L_{\mathrm{ur}}/K_{\mathrm{ur}}$. Similarly, we have the commutative diagram

$$\begin{array}{ccc} \bar{\mathcal{M}}_{L'\mathrm{ur}} & \xrightarrow{\pi_{L'\mathrm{ur}}} & \hat{\Omega}^1_{O_{L'_{\mathrm{ur}}}} \\ \Big\downarrow j'_{\mathrm{ur}} & & \Big\downarrow \mathrm{Tr}' \\ \bar{\mathcal{M}}_{K'\mathrm{ur}} & \xrightarrow{\pi_{K'\mathrm{ur}}} & \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}} \end{array} \tag{3.6}$$

We have already seen that $\pi_{L\mathrm{ur}}$, $\pi_{L'\mathrm{ur}}$, j_{ur} and j'_{ur} are surjective. The traces Tr and Tr' are also surjective. Indeed, suppose t_L, resp. t_K, are uniformising elements for L, resp. K. Then

$$\hat{\Omega}^1_{O_{L_{\mathrm{ur}}}} = \{f\,\mathrm{d}(t_L) \mid f \in \hat{O}_{L_{\mathrm{ur}}}\} = \{g\,\mathrm{d}(t_K) \mid g \in \mathcal{D}(L/K)^{-1}\hat{O}_{L_{\mathrm{ur}}}\},$$

where $\mathcal{D}(L/K)$ is the different of the extension L/K. It remains to notice that $\mathrm{Tr}(\mathcal{D}(L/K)^{-1}\hat{O}_{L_{\mathrm{ur}}}) = \hat{O}_{K_{\mathrm{ur}}}$.

Because $g_{LL'}$ and $f_{KK'}$ are comparable, we have the following commutative diagram

$$
\begin{array}{ccc}
\bar{\mathcal{M}}_{L\mathrm{ur}} & \xrightarrow{g_{LL'\mathrm{ur}}} & \bar{\mathcal{M}}_{L'\mathrm{ur}} \\
\Big\downarrow j_{\mathrm{ur}} & & \Big\downarrow j'_{\mathrm{ur}} \\
\bar{\mathcal{M}}_{K\mathrm{ur}} & \xrightarrow{f_{KK'\mathrm{ur}}} & \bar{\mathcal{M}}_{K'\mathrm{ur}}
\end{array}
\tag{3.7}
$$

Suppose $\omega_K \in \hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$. As it has been proved there is an $\omega_L \in \hat{\Omega}^1_{O_{L_{\mathrm{ur}}}}$ such that

$$\mathrm{Tr}(\omega_L) = \sum_{\tau \in I_{L/K}} \Omega(\tau)(\omega_L) = \omega_K.$$

Then

$$
\begin{aligned}
g_{LL'\infty}(\omega_K) &= \sum_{\tau \in I_{L/K}} g_{LL'\infty}(\Omega(\tau)(\omega_L)) \\
&= \sum_{\tau' \in I_{L'/K'}} \Omega(\tau')(g_{LL'\infty}(\omega_L)) = \mathrm{Tr}'(g_{LL'\infty}(\omega_L)) \in \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}
\end{aligned}
\tag{3.8}
$$

because $\Omega(\tau) g_{LL'\infty} = g_{LL'\infty}\Omega(\kappa(\tau))$, for any $\tau \in I_{L/K}$. This equality is implied by the following computations (we use the commutative diagrams (3.3), (3.4) and condition **C**)

$$
\begin{aligned}
\pi_{L\mathrm{ur}}\Omega(\tau) g_{LL'\infty} &= \tau^* \pi_{L\mathrm{ur}} g_{LL'\infty} = \tau^* g_{LL'\mathrm{ur}} \pi_{L'\mathrm{ur}} \\
&= g_{LL'\mathrm{ur}} \kappa(\tau)^* \pi_{L'\mathrm{ur}} = g_{LL'\mathrm{ur}} \pi_{L'\mathrm{ur}} \Omega(\kappa(\tau)) \\
&= \pi_{L\mathrm{ur}} g_{LL'\infty} \Omega(\kappa(\tau)),
\end{aligned}
$$

because $\pi_{L_{\mathrm{ur}}}$ is surjective.

Let $f_{KK'\infty}$ be the restriction of $g_{LL'\infty}$ on $\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}$. Then formula (3.8) implies that $f_{KK'\infty}(\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}}) \subset \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}$ and we have the following commutative diagram

$$
\begin{array}{ccc}
\hat{\Omega}^1_{O_{L_{\mathrm{ur}}}} & \xrightarrow{g_{LL'\infty}} & \hat{\Omega}^1_{O_{L'_{\mathrm{ur}}}} \\
\Big\downarrow \mathrm{Tr} & & \Big\downarrow \mathrm{Tr}' \\
\hat{\Omega}^1_{O_{K_{\mathrm{ur}}}} & \xrightarrow{f_{KK'\infty}} & \hat{\Omega}^1_{O_{K'_{\mathrm{ur}}}}
\end{array}
\tag{3.9}
$$

We now verify that $f_{KK'\infty}$ satisfies the requirements **A1-A3** from n.3.3. Property **A1** means that we have the following commutative diagram

$$\begin{array}{ccc} \bar{\mathcal{M}}_{K_{\rm ur}} & \xrightarrow{f_{KK'{\rm ur}}} & \bar{\mathcal{M}}_{K'_{\rm ur}} \\ \Big\downarrow \pi_{K_{\rm ur}} & & \Big\downarrow \pi_{K'_{\rm ur}} \\ \hat{\Omega}^1_{O_{K_{\rm ur}}} & \xrightarrow{f_{KK'\infty}} & \hat{\Omega}^1_{O_{K'_{\rm ur}}} \end{array}$$

Its commutativity is implied by the following computations (we use commutative diagrams (3.2), (3.5), (3.3) and (3.9))

$$\begin{aligned} j_{\rm ur} f_{KK'{\rm ur}} \pi_{K'{\rm ur}} &= g_{LL'{\rm ur}} j'_{\rm ur} \pi_{K'{\rm ur}} = g_{LL'{\rm ur}} \pi_{L'{\rm ur}} {\rm Tr}' \\ &= \pi_{L{\rm ur}} g_{LL'\infty} {\rm Tr}' = \pi_{L{\rm ur}} {\rm Tr} f_{KK'\infty} = j_{\rm ur} \pi_{K{\rm ur}} f_{KK'\infty} \end{aligned}$$

because $j_{\rm ur}$ is surjective.

Let C_K, $C_{K'}$, C_L and $C_{L'}$ be the Cartier operators on, resp., $\hat{\Omega}^1_{O_{K_{\rm ur}}}$, $\hat{\Omega}^1_{O_{K'_{\rm ur}}}$, $\hat{\Omega}^1_{O_{L_{\rm ur}}}$ and $\hat{\Omega}^1_{O_{L'_{\rm ur}}}$. Clearly, $C_L {\rm Tr} = {\rm Tr} C_K$ and $C_{L'} {\rm Tr}' = {\rm Tr}' C_{K'}$. Then it follows from the commutative diagram (3.9) and property **A2** for $g_{LL'\infty}$ that

$$\begin{aligned} {\rm Tr} C_K f_{KK'\infty} &= C_L {\rm Tr} f_{KK'\infty} = C_L g_{LL'\infty} {\rm Tr} \\ &= g_{LL'\infty} C_{L'} {\rm Tr} = g_{LL'\infty} {\rm Tr} C_{K'} = {\rm Tr} f_{KK'\infty} C_{K'}. \end{aligned}$$

Property **A2** for $f_{KK'\infty}$ follows because Tr is surjective.

By condition **C**, the ramification indices e and e' of the extensions $L_{\rm ur}/K_{\rm ur}$ and $L'_{\rm ur}/K'_{\rm ur}$ are equal. Then we use the condition **A3** for $g_{LL'\infty}$ to deduce that for any $n \geqslant 0$,

$$g_{LL'\infty}(t_K^n \hat{\Omega}^1_{O_{L_{\rm ur}}}) = g_{LL'\infty}(t_L^{en} \hat{\Omega}^1_{O_{L_{\rm ur}}}) = t_L'^{e'n} \hat{\Omega}^1_{O_{L'_{\rm ur}}} = t_{K'}^n \hat{\Omega}^1_{O_{L'_{\rm ur}}}.$$

Therefore, it follows from the commutativity of diagram (3.9) that

$$\begin{aligned} t_{K'}^n \hat{\Omega}^1_{O_{K'_{\rm ur}}} &= t_{K'}^n {\rm Tr}'(\hat{\Omega}^1_{O_{L'_{\rm ur}}}) = {\rm Tr}'(g_{LL'\infty}(t_K^n \hat{\Omega}^1_{O_{L_{\rm ur}}})) \\ &= f_{KK'\infty}({\rm Tr}(t_K^n \hat{\Omega}^1_{O_{L_{\rm ur}}})) = f_{KK'\infty}(t_{K'}^n \hat{\Omega}^1_{O_{K_{\rm ur}}}). \end{aligned}$$

The proposition is proved. □

Remark. Using the embeddings of the Galois groups $\Gamma_{L_s}(p)$ and $\Gamma_{K_s}(p)$ into their Magnus's algebras from n.1.3, one can prove in addition that if $g_{LL'}$ is special then $f_{KK'}$ is also special. In other words, under condition **C**, $j_{\rm ur}(\mathcal{M}_{L\infty}) \subset \mathcal{M}_{K\infty}$.

Suppose $g_{LL'}$ and $f_{KK'}$ are comparable systems. Suppose also that $g_{LL'}$ and $f_{KK'}$ are special admissible, locally analytic and satisfy condition **C**. Then there are $\eta_{LL'} \in {\rm Iso}^0(L, L')$ and $\eta_{KK'} \in {\rm Iso}^0(K, K')$ such that $f_{KK'\infty}|_{{\rm d}\, \hat{O}_{K_{\rm ur}}} = {\rm d}(\eta_{KK'}) \hat{\otimes}_k k(p)$ and $g_{LL'\infty}|_{{\rm d}\, \hat{O}_{L_{\rm ur}}} = {\rm d}(\eta_{LL'}) \hat{\otimes}_{k_L} k_L(p)$.

Proposition 3.6. *With the above notation and assumptions,* $\eta_{LL'}|_K = \eta_{KK'}$.

Proof. Clearly, for any $\tau \in I_{L/K}$, condition **C** implies that $\tau^*_{LL\infty} g_{LL'\infty} = g_{LL'\infty}\kappa(\tau)^*_{L'L'\infty}$. Restricting this equality to $\mathrm{d}\,\hat{O}_{L_{\mathrm{ur}}}$, we obtain

$$\mathrm{d}(\tau)\,\mathrm{d}(\eta_{LL'}) = \mathrm{d}(\eta_{LL'})\,\mathrm{d}(\kappa(\tau)).$$

Then it follows from proposition 2.7 that $\tau\eta_{LL'} = \eta_{LL'}\kappa(\tau)$. Therefore, $\eta_{LL'}|_K$ induces a ring isomorphism from $\hat{O}_{K_{\mathrm{ur}}}$ onto $\hat{O}_{K'_{\mathrm{ur}}}$.

Suppose $a \in \mathrm{Tr}(\hat{O}_{L_{\mathrm{ur}}}) \subset \hat{O}_{K_{\mathrm{ur}}}$. If $a = \mathrm{Tr}(b)$ with $b \in \hat{O}_{L_{\mathrm{ur}}}$ then it follows from diagram (3.9) and condition **C** that

$$\mathrm{d}(\eta_{KK'}(a)) = \mathrm{Tr}'(\mathrm{d}(\eta_{LL'}(b))) = \sum_{\tau' \in I_{L'/K'}} \mathrm{d}(\tau')\,(\mathrm{d}(\eta_{LL'}(b)))$$

$$= \sum_{\tau \in I_{L/K}} \mathrm{d}(\eta_{LL'})(\mathrm{d}(\tau(b))) = \mathrm{d}\,\eta_{LL'}(\mathrm{d}\,a) = \mathrm{d}(\eta_{LL'}(a)).$$

Therefore, for a sufficiently large $M \in \mathbb{N}$, $\mathrm{d}\,(\eta_{LL'}|_K)$ and $\mathrm{d}\,\eta_{KK'}$ coincide on $t_K^M\hat{O}_{K_{\mathrm{ur}}}$. Then proposition 2.7 implies that $\eta_{LL'}|_K = \eta_{KK'}$.

The proposition is proved. □

4. Explicit description of the ramification ideals $\mathcal{A}^{(v)}$ mod $\mathcal{J}^3$

We return to the notation from Section 1. In particular, $\mathcal{A}$ is the $\mathbb{Z}_p$-algebra from Subsection 1.2, $\mathcal{J}$ is its augmentation ideal, $\mathcal{A}_k = \mathcal{A}\otimes W(k)$, $\mathcal{J}_k = \mathcal{J}\otimes W(k)$, $\mathcal{A}_K = \mathcal{A}\otimes O(K)$, etc. are the corresponding extensions of scalars, $e \in \mathcal{A}_K$ is the element introduced in Subsection 1.3. We fix an $f \in \mathcal{A}_{K(p)}$ such that $\sigma f = fe$ and denote the embedding $\psi_f : \Gamma(p) \longrightarrow (1+\mathcal{J})^\times$ by ψ.

4.1. Ramification filtration on $\mathcal{A}$

For any $v \geqslant 0$, consider the ramification subgroup $\Gamma(p)^{(v)}$ of $\Gamma(p)$ in the upper numbering. Denote by $\mathcal{A}^{(v)}$ the minimal 2-sided closed ideal in $\mathcal{A}$ containing the elements $\psi(\tau)-1$, for all $\tau \in \Gamma(p)^{(v)}$. Then $\{\mathcal{A}^{(v)} \mid v \geqslant 0\}$ is a decreasing filtration by closed ideals of $\mathcal{A}$. In particular, if $\mathcal{A}^{(v)}_{CM} \bmod \mathcal{J}^n_{CM}$ are the projections of $\mathcal{A}^{(v)}$ to $\mathcal{A}_{CM} \bmod \mathcal{J}^n_{CM}$, for $C, M, n \in \mathbb{N}$, then $\mathcal{A}^{(v)} = \varprojlim_{C,M,n} \mathcal{A}^{(v)}_{CM} \bmod \mathcal{J}^n_{CM}$. Notice also that the ramification filtration $\{\Gamma(p)^{(v)}\}_{v\geqslant 0}$ is left-continuous, i.e. $\Gamma(p)^{(v_0)} = \bigcap_{v<v_0} \Gamma(p)^{(v)}$, for any $v_0 > 0$. This implies a corresponding analogous property for the filtration $\{\mathcal{A}^{(v)} \mid v \geqslant 0\}$ on each finite level, i.e. for any $C, M, n \in \mathbb{N}$, we have the following property.

Proposition 4.1. *For any $C, M, n \in \mathbb{N}$ and $v_0 > 0$, there is a $0 < \delta < v_0$ such that $\mathcal{A}_{CM}^{(v)} \operatorname{mod} \mathcal{J}_{CM}^n = \mathcal{A}_{CM}^{(v_0)} \operatorname{mod} \mathcal{J}_{CM}^n$, for any $v \in (v_0 - \delta, v_0)$.*

Proof. This follows directly from the definition of the ramification filtration and the fact that the field of definition of each projection $f_{CM} \operatorname{mod} \mathcal{J}_{CM}^n$ of f to $\mathcal{A}_{CMK(p)} \operatorname{mod} \mathcal{J}_{CMK(p)}^n$ is a finite extension of K, cf. Subsection 1.3. □

Notice also that the class field theory implies the following property.

Proposition 4.2. *If $v \geqslant 0$ and $\mathcal{A}_k^{(v)} := \mathcal{A}^{(v)} \otimes W(k)$ then $\mathcal{A}_k^{(v)} \operatorname{mod} \mathcal{J}_k^2$ is topologically generated by all elements $p^s D_{an}$, for $n \in \mathbb{Z} \operatorname{mod} N_0$, $a \in \mathbb{Z}(p)$, $s \geqslant 0$ and $p^s a \geqslant v$.*

4.2. The filtration $\mathcal{A}(v)$, $v \geqslant 0$. For any $\gamma \geqslant 0$, introduce $\mathcal{F}_\gamma \in \mathcal{A}_k$ as follows.

If $\gamma = 0$ let $\mathcal{F}_\gamma = D_0$.

If $\gamma > 0$ let $\mathcal{F}_\gamma =$

$$p^{v_\gamma} a_\gamma D_{a_\gamma v_\gamma} - \sum_{\substack{a_1, a_2 \in \mathbb{Z}(p) \\ n \geqslant 0 \\ p^n(a_1 + a_2) = \gamma}} p^n a_1 D_{a_1 n} D_{a_2 n} - \sum_{\substack{a_1, a_2 \in \mathbb{Z}(p) \\ n_1 \geqslant 0, n_2 < n_1 \\ p^{n_1} a_1 + p^{n_2} a_2 = \gamma}} p^{n_1} a_1 [D_{a_1 n_1}, D_{a_2 n_2}].$$

Here the first two terms appear only if $\gamma \in \mathbb{N}$, and the corresponding $v_\gamma \in \mathbb{Z}_{\geqslant 0}$ and $a_\gamma \in \mathbb{Z}(p)$ are uniquely determined from the equality $\gamma = p^{v_\gamma} a_\gamma$. If $\gamma \notin \mathbb{Z}$ then the above formula for $\mathcal{F}_\gamma$ contains only the last sum.

For any $v \geqslant 0$, let $\mathcal{A}(v)$ be the minimal closed ideal in $\mathcal{A}$ such that $\mathcal{F}_\gamma \in \mathcal{A}_k(v) := \mathcal{A}(v) \otimes W(k)$, for all $\gamma \geqslant v$. Equivalently, $\mathcal{A}_k(v)$ is the minimal σ-invariant closed ideal of $\mathcal{A}_k$, which contains all $\mathcal{F}_\gamma$ with $\gamma \geqslant v$.

Remark. a) For any $v \geqslant 0$, $\mathcal{A}^{(v)} \operatorname{mod} \mathcal{J}^2 = \mathcal{A}(v) \operatorname{mod} \mathcal{J}^2$.

b) The filtration $\{\mathcal{A}(v) \mid v \geqslant 0\}$ is left-continuous.

c) If $C, M \in \mathbb{N}$ and $\mathcal{A}_{CM}(v) \operatorname{mod} \mathcal{J}_{CM}^n$ is the image of $\mathcal{A}(v)$ in $\mathcal{A}_{CM} \operatorname{mod} \mathcal{J}_{CM}^n$, then $\mathcal{A}(v) \operatorname{mod} \mathcal{J}^n = \varprojlim_{C,M} \mathcal{A}_{CM}(v) \operatorname{mod} \mathcal{J}_{CM}^n$.

If $\gamma \geqslant v_0 \geqslant 0$, denote by $\tilde{\mathcal{F}}_\gamma(v_0)$ the elements in $\mathcal{A}_k$ given by the same expressions as $\mathcal{F}_\gamma$ but with the additional restriction $p^{n_1} a_1, p^{n_1} a_2 < v_0$ for all degree 2 terms $p^{n_1} a_1 D_{a_1 n_1} D_{a_2 n_2}$ or $p^{n_1} a_1 [D_{a_1 n_1}, D_{a_2, n_2}]$. Clearly, we have the following property.

Proposition 4.3. a*) $\mathcal{A}(v_0)$ operatornamemod$\mathcal{J}^3$ is the minimal ideal of $\mathcal{A}$ such that $\mathcal{A}_k(v_0)$ is generated by all elements $\tilde{\mathcal{F}}_\gamma(v_0)$ with $\gamma \geqslant v_0$.*

b*) If $\gamma \geqslant 2v_0$, then $\tilde{\mathcal{F}}_\gamma(v_0) = \gamma D_{a_\gamma v_\gamma}$.*

The following theorem is the main technical result about the structure of the ramification filtration that we need in this paper.

Theorem B. *For any* $v \geqslant 0$, $\mathcal{A}^{(v)} \bmod \mathcal{J}^3 = \mathcal{A}(v) \bmod \mathcal{J}^3$.

This theorem gives an explicit description of the ramification filtration $\{\mathcal{A}^{(v)}\}_{v\geqslant 0}$ on the level of p-extensions of nilpotent class 2. (On the level of abelian p-extensions such a description is given by the above Remark a).) Theorem B can also be stated in the following equivalent form, where we use the index $M+1$ instead of M to simplify the notation in its proof below.

Theorem B'. *Suppose* $C \in \mathbb{N}$, $M \in \mathbb{Z}_{\geqslant 0}$ *and* $v_0 > 0$. *If, for all* $v > v_0$,

$$\mathcal{A}^{(v)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(v) \bmod \mathcal{J}^3_{C,M+1},$$

then

$$\mathcal{A}^{(v_0)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(v_0) \bmod \mathcal{J}^3_{C,M+1}.$$

Clearly, Theorem B' follows from theorem B.

Conversely, notice first that, for a given $C \in \mathbb{N}$, $M \geqslant 0$ and $v \gg 0$,

$$\mathcal{A}^{(v)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(v) \bmod \mathcal{J}^3_{C,M+1} = 0.$$

Indeed, this is obvious for the ideals $\mathcal{A}_{C,M}(v)$, because they are generated by the elements obtained from the above elements $\tilde{\mathcal{F}}_\gamma(v)$ by adding the restrictions $a_1, a_2, a_\gamma < C$ and $n_1, n_2, v_\gamma \leqslant M$. But then, for $\gamma \geqslant 2p^M C$, the conditions $p^{n_1}a_1 + p^{n_2}a_2 = \gamma$ (where $n_2 \leqslant n_1$) and $p^{v_\gamma}a_\gamma = \gamma$ are never satisfied. For the filtration $\{\mathcal{A}^{(v)}\}_{v\geqslant 0}$, we notice, as earlier, that the field of definition $K_{C,M+1,3}(f)$ of the image of f in $\mathcal{A}_{C,M+1,K(p)} \bmod \mathcal{J}^3_{C,M+1,K(p)}$ is of finite degree over the basic field K. Therefore, for $v \gg 0$, the ramification subgroup $\Gamma(p)^{(v)}$ acts trivially on $K_{C,M+1,3}(f)$ and $\mathcal{A}^{(v)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = 0$.

Now we can apply descending transfinite induction on $v \geqslant 0$. Let

$$S_{C,M+1} = \{v \geqslant 0 \mid \mathcal{A}^{(v)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(v) \bmod \mathcal{J}^3_{C,M+1}\}.$$

Then $S_{C,M+1} \neq \emptyset$. Let $v_0 = \inf S_{C,M+1}$.

If $v_0 > 0$ then $\mathcal{A}^{(v_0)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{CM}(v_0) \bmod \mathcal{J}^3_{C,M+1}$ by Theorem B'. By the left-continuity property of both filtrations, there is a $\delta \in (0, v_0)$ such that $\mathcal{A}^{(v)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(v) \bmod \mathcal{J}^3_{C,M+1}$ whenever $v \in (v_0 - \delta, v_0)$. So, $v_0 = \inf S_{C,M+1} \leqslant v_0 - \delta$. This is a contradiction, hence $v_0 = 0$. In this case we have $\mathcal{A}^{(0)}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1} \bmod \mathcal{J}^3_{C,M+1} = \mathcal{A}_{C,M+1}(0) \bmod \mathcal{J}^3_{C,M+1}$. This implies that $S_{C,M+1} = \mathbb{R}_{\geqslant 0}$, and Theorem B is deduced from Theorem B'.

The rest of this section is concerned with a proof of Theorem B'.

4.3. Auxiliary results.

4.3.1. ***The field $K(N^*, r^*)$.*** Suppose $N^* \in \mathbb{N}$, $q = p^{N^*}$ and $r^* = m^*/(q-1)$, where $m^* \in \mathbb{Z}(p)$. Then there is a field $K_1 := K(N^*, r^*) \subset K_{\mathrm{sep}}$ such that

a) $[K_1 : K] = q$;

b) the Herbrand function $\varphi_{K_1/K}(x)$ has only one corner point (r^*, r^*);

c) $K_1 = k((t_{K_1}))$, where $t_{K_1}^q E(-1, t_{K_1}^{m^*}) = t_K$ and E is the generalised Artin-Hasse exponential introduced in n.1.4.

The field $K(N^*, r^*)$ appears as a subfield of $K(U)$, where $U^q - U = u^{-m^*}$ and $u^{q-1} = t_K$. It is of degree q over K. Its construction is explained in all detail in [2].

4.3.2. ***Relation between liftings of K and K_1 modulo p^{M+1}, $M \geqslant 0$.*** Recall that we use the uniformiser t_K in K to construct the liftings modulo p^{M+1} of K, $O_{M+1}(K) = W_{M+1}(k)((t))$ and of $K(p)$, $O_{M+1}(K(p))$, where $t = t_{K,M+1}$. We use the uniformiser t_{K_1} from above n.4.3.1 c) to construct analogous liftings for K_1, $O'_{M+1}(K_1) = W_{M+1}(k)((t_1))$ and for $K_1(p) \supset K(p)$, $O'_{M+1}(K_1(p))$. (Here $t_1 = t_{K_1,M+1}$ is the Teichmüller representative of t_{K_1} in $W_{M+1}(K_1(p))$.)

Note that, with the above notation the field embedding $K \subset K_1$ does not induce an embedding $O_{M+1}(K) \subset O'_{M+1}(K_1)$ for $M \geqslant 1$, because the Teichmüller representative $t_1 = t_{K_1,M+1} = [t_{K_1}]$ cannot be expressed in terms of the Teichmüller representative $t = t_{K,M+1} = [t_K]$. This difficulty can be overcome as follows. Take $t_K^{p^M}$ as a uniformising element for $\sigma^M K$ and consider the corresponding liftings modulo p^{M+1}, $O_{M+1}(\sigma^M K) = W_{M+1}(k)((t^{p^M}))$ and $O_{M+1}(\sigma^M K(p)) \subset O_{M+1}(K(p))$. From the definition of liftings it follows that

$$O_{M+1}(\sigma^M K) \subset W_{M+1}(\sigma^M K) \subset W_{M+1}(\sigma^M K_1) \subset O'_{M+1}(K_1) \subset W_{M+1}(K_1),$$

$$O_{M+1}(\sigma^M K(p)) \subset W_{M+1}(\sigma^M K(p)) \subset W_{M+1}(\sigma^M K_1(p)) \subset O'_{M+1}(K_1(p)) \subset W_{M+1}(K_1(p)).$$

Lemma 4.4. *With respect to the above embedding $O_{M+1}(\sigma^M K) \subset O'_{M+1}(K_1)$ we have*

$$t^{p^M} = t_1^{qp^M} E(-1, t_1^{m^*})^{p^M}.$$

Proof. If V is the Verschiebung morphism on $W_{M+1}(K_1)$ then property c) from n.4.3.1 is equivalent to the relation

$$t \equiv t_1^{qp^M} E(-1, t_1^{m^*}) \bmod V W_{M+1}(K_1).$$

Then, for any $s \geqslant 0$, we have

$$t^{p^s} \equiv t_1^{qp^s} E(-1, t_1^{m^*})^{p^s} \operatorname{mod} V^{s+1} W_{M+1}(K_1).$$

(Using that for any $w_1, w_2 \in W_M(K_1)$, $(Vw_1)(Vw_2) = V^2(F(w_1w_2))$ and $pV(w_1) = V^2(Fw_1)$.) For $s = M$ we obtain the statement of the lemma. □

4.3.3. *A criterion.* Consider $\sigma^M e = 1 + \sum_{a \in \mathbb{Z}^0(p)} t^{-ap^M} D_{a,M} \in \mathcal{A} \otimes O(\sigma^M K)$, where $O(\sigma^M K) = \varprojlim_n O_n(\sigma^M K)$. Then $\sigma^M f \in \mathcal{A} \otimes O(\sigma^M K(p))$ satisfies the relation $\sigma(\sigma^M f) = (\sigma^M f)(\sigma^M e)$ and induces the same morphism $\psi : \Gamma(p) \longrightarrow \mathcal{A}$ as f. Indeed, for any $\tau \in \Gamma(p)$,

$$\tau(\sigma^M f)(\sigma^M f)^{-1} = \sigma^M(\tau(f)f^{-1}) = \sigma^M(\psi(\tau)) = \psi(\tau)$$

because σ acts trivially on $\mathcal{A}$.

This means that we can still study the structure of the ramification filtration $\{\mathcal{A}^{(v)} \operatorname{mod} p^{M+1}\}_{v \geqslant 0}$ by working inside the lifting $O'_{M+1}(K_1(p)) \supset O_{M+1}(\sigma^M K(p))$ associated with our auxiliary field K_1 and its uniformiser t_{K_1}.

Set $\mathcal{B} = \mathcal{A}_{C,M+1} \operatorname{mod} \mathcal{J}^3_{C,M+1}$ and for any rational number $v \geqslant 0$, $\mathcal{B}^{(v)} = \mathcal{A}^{(v)}_{C,M+1} \operatorname{mod} \mathcal{J}_{C,M+1}$. We shall also use the notation $\mathcal{B}_k = \mathcal{B} \otimes W_{M+1}(k)$, $\mathcal{B}_{K_1} = \mathcal{B} \otimes O'_{M+1}(K_1)$, and $\mathcal{B}_{K_1(p)} = \mathcal{B} \otimes O'_{M+1}(K_1(p))$. Denote again by $\mathcal{J}$ the augmentation ideal in $\mathcal{B}$. Its extensions of scalars will be denoted similarly by $\mathcal{J}_k, \mathcal{J}_{K_1}$ and $\mathcal{J}_{K_1(p)}$.

Consider an abstract continuous field isomorphism $\alpha : K \longrightarrow K_1$, which is the identity on the residue fields and sends t_K to t_{K_1}. Consider its extension to the field isomorphism $\hat{\alpha} : K(p) \longrightarrow K_1(p)$. Then we have an induced isomorphism of liftings $\hat{\alpha} : O_{M+1}(K(p)) \longrightarrow O'_{M+1}(K_1(p))$. Use it to define the morphism

$$\mathrm{id} \otimes \hat{\alpha} : \mathcal{A}_{C,M+1,K(p)} \longrightarrow \mathcal{B}_{K_1(p)}$$

and set $f_1 := (\mathrm{id} \otimes \hat{\alpha})(f) \in \mathcal{B}_{K_1(p)}$. Then $\sigma(f_1) = f_1 e_1$, where $e_1 = (\mathrm{id} \otimes \hat{\alpha})(e) = 1 + \sum_{a \in \mathbb{Z}^0(p)} t_1^{-a} D_{a0}$.

If $N^* \equiv 0 \operatorname{mod} N_0$, then $\sigma^{M+N^*}(D_{a0}) = \sigma^M(D_{a0}) = D_{aM}$ and we can relate the elements $\sigma^M e = 1 + \sum_{a \in \mathbb{Z}^0(p)} t^{-ap^M} D_{a,M}$ and $\sigma^{M+N^*} e_1 = 1 + \sum_{a \in \mathbb{Z}^0(p)} t_1^{-ap^M q} D_{a,M}$ by the use of the relation between t and t_1 from lemma 4.4. So, it will be natural to compare the elements $\sigma^M f$ and $\sigma^{M+N^*} f_1$ in $\mathcal{B}_{K_1(p)}$ by introducing $X \in \mathcal{B}_{K_1(p)}$ such that $(\sigma^M f)(1 + X) = \sigma^{M+N^*} f_1$. This element will be used for the characterisation of the ideal $\mathcal{B}^{(v_0)}$ in proposition 4.5 below.

Notice first, that $\mathcal{B}^{(v_0)}$ is the minimal 2-sided ideal in $\mathcal{B}$ such that the field of definition of $f \operatorname{mod} \mathcal{B}^{(v_0)}_{K_1(p)}$ is invariant under the action of the group

$\Gamma(p)^{(v_0)}$. In other words, if I is a 2-sided ideal in $\mathcal{B}$ and $K(f,I)$ is the field of definition of $f \bmod I_{K_1(p)}$, then I contains $\mathcal{B}^{(v_0)}$ if and only if the largest upper ramification number $v(K(f,I)/K)$ (= the 2nd coordinate of the last vertex of the graph of the Herbrand function $\varphi_{K(f,I)/K}$) is less than v_0.

With the above notation we have the following criterion.

Proposition 4.5. *Suppose $r^* = v(K_1/K) < v_0$. Then $\mathcal{B}^{(v_0)}$ is the minimal element in the set of all 2-sided ideals I such that if $K_1(X,I)$ is the field of definition of $X \bmod I_{K_1(p)}$ over K_1 then its largest upper ramification number satisfies $v(K_1(X,I)/K_1) < qv_0 - r^*(q-1)$.*

Proof. We must prove that for any 2-sided ideal I in $\mathcal{B}$,

$$v := v(K(f,I)/K) < v_0 \quad \Leftrightarrow \quad v_1(X) := v(K_1(X,I)/K_1) < qv_0 - r^*(q-1).$$

The following proof is similar to the proof of the corresponding statement from [1, 2].

Suppose $v < v_0$. The existence of the field isomorphism $\hat{\alpha}$ implies that $v(K_1(f_1,I)/K_1) = v$. Then

$$v_1 := v(K_1(f_1,I)/K) = \max\{r^*, \varphi_{K_1/K}(v)\} \tag{4.1}$$

Indeed, it is sufficient to look at the maximal vertex of the Herbrand function for the extension $K_1(f_1,I)/K$ and to use the composition property for the corresponding Herbrand functions $\varphi_{K_1(f_1,I)/K}(x) = \varphi_{K_1/K}(\varphi_{K_1(f_1,I)/K_1}(x))$. This implies that $v_1 = r^*$ if $r^* \geqslant v$ and $v_1 < v$ if $v > r^*$, where we have used that $\varphi_{K_1/K}(v) = r^* + (v - r^*)/q < v$ if $v > r^*$. Therefore, the largest upper ramification number of the composite $K(f,I)$ and $K_1(f_1,I)$ over K is $\max\{r^*, v\} < v_0$. Clearly, $K_1(X,I)$ is contained in this composite and, therefore, $v(X) := v(K_1(X,I)/K) < v_0$. Similarly to formula (4.1) we obtain that $v(X) = \max\{r^*, \varphi_{K_1/K}(v_1(X))\}$. Therefore, $\varphi_{K_1/K}(v_1(X)) < v_0$ and $v_1(X) < qv_0 - r^*(q-1)$.

Conversely, assume that $v_1(X) < qv_0 - r^*(q-1)$. Then

$$v(X) = \max\{r^*, \varphi_{K_1/K}(v_1(X))\} < v_0.$$

Suppose $v = v(K(f,I)/K) \geqslant v_0$. As earlier, the existence of $\hat{\alpha}$ implies that $v(K_1(f_1,I)/K_1) = v$ and similarly to (4.1) we have

$$v(K_1(f_1,I)/K) = \max\{r^*, \varphi_{K_1/K}(v)\} = \varphi_{K_1/K}(v) < v.$$

Therefore, the largest upper ramification number of the composite of $K_1(X,I)$ and $K_1(f_1,I)$ over K equals

$$\max\{v(K_1(X,I)/K), v(K_1(f_1,I)/K)\} = \max\{v(X), \varphi_{K_1/K}(v)\}.$$

Because $K(f,I)$ is contained in this composite, we have

$$v \leqslant \max\{v(X), \varphi_{K_1/K}(v)\}.$$

But $v \geqslant v_0 > v(X)$ and $v > \varphi_{K_1/K}(v)$. This contradiction proves the proposition. . □

4.3.4. ***Choosing N^* and r^*.*** In order to apply the criterion from Proposition 4.5 we shall use the special choice of $K_1 = K(N^*, r^*)$, where $N^* \in \mathbb{N}$ and $r^* < v_0$ are specified as follows.

Introduce $\delta_1 := \min\{v_0 - p^s a \mid p^s a < v_0, a \leqslant C, a \in \mathbb{Z}^0(p)\}$, and $\delta_2 :=$

$$\min\{v_0 - (p^{s_1}a_1 + p^{s_2}a_2) | \\ p^{s_1}a_1 + p^{s_2}a_2 < v_0, a_1, a_2 \leqslant C, a_1, a_2 \in \mathbb{Z}^0(p), s_1, s_2 \in \mathbb{Z}\}.$$

One can see that for a sufficiently large natural number $N^* \equiv 0 \bmod N_0$, there exists $r^* = m^*/(q-1) < v_0$ with $q = p^{N^*}$ and $m^* \in \mathbb{Z}(p)$ such that

a) $-(v_0 - \delta_1)q + r^*(q-1) > Cp^M$;

b) $-(v_0 - \delta_2)q + r^*(q-1) > 0$;

c) $v_0 q < 2r^*(q-1)$.

So, we may assume that $K_1 = K(N^*, r^*)$ where $N^* \equiv 0 \bmod N_0$ and the above inequalities a)-c) hold.

4.4. A recurrence formula for *X*. Set $\Theta^* = t_1^{r^*(q-1)}$. Then

$$\omega = \sigma^M e - \sigma^{M+N^*} e_1 = \sum_{a \in \mathbb{Z}^0(p)} t_1^{-ap^M q} (E(a, \Theta^*)^{p^M} - 1) D_{aM} \in \mathcal{J}_{K_1}.$$

The relation $1 + X = (\sigma^M f)^{-1}(\sigma^{M+N^*} f_1)$ implies that

$$1 + \sigma X = (\sigma^M e)^{-1}(1 + X)(\sigma^{M+N^*} e_1)$$

and

$$X - \sigma X = \omega + (\sigma^M e - 1)\sigma X - X(\sigma^{M+N^*} e_1 - 1). \tag{4.2}$$

If $\bar{X} := X \bmod \mathcal{J}^2_{K_1(p)}$, then the above relation (4.2) gives $\bar{X} - \sigma\bar{X} = \omega \bmod \mathcal{J}^2_{K_1(p)}$. We shall use this relation in Subsection 4.5 below to study $\bar{X}$. Now (4.2) can be rewritten as

$$X - \sigma X = \omega - \omega(\sigma^{M+N^*} e_1 - 1) - [\sigma\bar{X}, \sigma^{M+N^*} e_1 - 1] + \omega\sigma(\bar{X}), \tag{4.3}$$

using that $X \equiv \omega + \sigma X \bmod \mathcal{J}^2_{K_1(p)}$. We shall use this relation in nn.4.6-4.7 below to study the field of definition of X.

4.5. The study of $\bar{X}$. For $0\leqslant r\leqslant M$ and $b\in\mathbb{Z}_p$, introduce $\mathcal{E}_r(b,T)\in\mathbb{Z}_p[[T]]$ as follows:

$\mathcal{E}_0(b,T)=E(b,T)-1$, where $E(b,T)$ is the generalisation of the Artin-Hasse exponential from n.1.4;

$\mathcal{E}_1(b,T)=E(b,T)^p-E(b,T^p)=(\exp(pbT)-1)E(b,T^p)$,

....

$\mathcal{E}_M(b,T)=E(b,T)^{p^M}-E(b,T^p)^{p^{M-1}}=(\exp(p^MbT)-1)E(b,T^p)^{p^{M-1}}$.

Notice the following simple properties:

(1) $E(b,T)^{p^M}-1=\mathcal{E}_0(b,T^{p^M})+\mathcal{E}_1(b,T^{p^{M-1}})+\dots+\mathcal{E}_M(b,T)$;

(2) $\mathcal{E}_r(b,T)=p^rT+p^rT^2g_r(T)$, where $0\leqslant r\leqslant M$ and $g_r\in\mathbb{Z}_p[[T]]$.

Consider the decomposition $\omega=\sum_{r+s=M}\sigma^r\omega_s$ (cf. Subsection 4.4 for the definition of ω), where

$$\omega_s:=\sum_{a\in\mathbb{Z}^0(p)}t_1^{-ap^sq}\mathcal{E}_s(a,\Theta^*)D_{as},$$

for $0\leqslant s\leqslant M$. Note that $p^sD_{as}\in\mathcal{B}_k^{(v_0)}\operatorname{mod}\mathcal{J}_k^2$, whenever $p^sa\geqslant v_0$, cf. proposition 4.2. Also, if $p^sa<v_0$ then $-ap^sq+r^*(q-1)>Cp^M$, cf. Subsubsection 4.3.4, and we have $t_1^{-ap^sq}\mathcal{E}_s(a,\Theta^*)\in t_1^{Cp^M}\mathrm{m}_1$, where $\mathrm{m}_1:=t_1W_M(k)[[t_1]]$.

So, for $0\leqslant s\leqslant M$,

$$\omega_s\in\mathcal{B}_{K_1}^{(v_0)}+t_1^{Cp^M}\mathcal{J}_{\mathrm{m}_1}+\mathcal{J}_{K_1}^2,\tag{4.4}$$

where $\mathcal{J}_{\mathrm{m}_1}=\mathcal{J}\otimes\mathrm{m}_1$.

For $0\leqslant s\leqslant M$, consider $X_s\in\mathcal{B}_{K_1(p)}$ such that $X_s-\sigma X_s=\omega_s$. Because of (4.4), we may assume that $X_s\equiv\sum_{u\geqslant0}\sigma^u\omega_s\operatorname{mod}(\mathcal{B}_{K_1(p)}^{(v_0)}+\mathcal{J}_{K_1(p)}^2)$. Notice that

$$\bar{X}\equiv\sum_{r+s=M}\sigma^r(X_s)\operatorname{mod}\mathcal{J}_{K_1(p)}^2,$$

and after replacing the infinite sum $\sum_{u\geqslant0}$ by its first (N^*-s) terms in the above congruence for X_s, we obtain

$$\bar{X}=\sum_{\substack{u+s\geqslant M\\ u<N^*}}\sigma^u\omega_s\operatorname{mod}(\mathcal{B}_{K_1(p)}^{(v_0)}+\mathcal{J}_{K_1(p)}^2+t_1^{Cp^Mq}\mathcal{J}_{\mathrm{m}_1}).\tag{4.5}$$

4.6. The study of X. From the above formulas (4.4) it follows that $\bar{X}$ and $\sigma(\bar{X})$ belong to $\mathcal{B}^{(v_0)}_{K_1(p)}+t_1^{Cp^M}\mathcal{J}_{\mathrm{m}_1}+\mathcal{J}^2_{K_1(p)}$. This implies that

$$\omega\sigma(\bar{X})\in\mathcal{B}^{(v_0)}_{K_1(p)}\mathcal{J}_{K_1(p)}+\mathcal{J}_{\mathrm{m}_1}.$$

Therefore, when solving equation (4.3) for X, this term will not have any influence on the field of definition of $X\bmod\mathcal{B}^{(v_0)}_{K_1(p)}\mathcal{J}_{K_1(p)}$.

For a similar reason, we may replace $\bar{X}$ in (4.3) by the right hand side from (4.5) without affecting the field of definition of $X\bmod\mathcal{B}^{(v_0)}_{K_1(p)}\mathcal{J}_{K_1(p)}$. The new right hand side will be then equal to

$$\begin{aligned}\sum_{\substack{a\in\mathbb{Z}^0(p)\\0\leqslant s\leqslant M}} & t_1^{-ap^Mq}\mathcal{E}_s(a,\Theta^{*p^{M-s}})\\ &-\sum_{\substack{a_1,a_2\in\mathbb{Z}^0(p)\\0\leqslant s\leqslant M}}t_1^{-(a_1+a_2)p^Mq}\mathcal{E}_s(a_1,\Theta^{*p^{M-s}})D_{a_1M}D_{a_2M}\\ &-\sum_{\substack{0\leqslant s_1\leqslant M,a_1,a_2\in\mathbb{Z}^0(p)\\N^*>u>M-s_1}}t_1^{-a_1p^{s_1+u}q-a_2p^Mq}\mathcal{E}_{s_1}(a_1,\Theta^{*p^u})[D_{a_1,s_1+u},D_{a_2,M}].\end{aligned}$$

Finally we can apply the Witt-Artin-Schreier equivalence to the last formula to deduce that modulo any ideal containing the ideal $\mathcal{B}^{(v_0)}_{K_1(p)}\mathcal{J}_{K_1(p)}$, the elements X and X', where $X'-\sigma X'=$

$$\sum_{0\leqslant s\leqslant M}t_1^{-ap^sq}\mathcal{E}_s(a_1,\Theta^*)D_{as}-\sum_{0\leqslant s\leqslant M}t_1^{-(a_1+a_2)p^sq}\mathcal{E}_s(a_1,\Theta^*)D_{a_1s}D_{a_2s}$$

$$-\sum_{\substack{0\leqslant s_1\leqslant M\\M-N^*<s_2<s_1}}t_1^{-(a_1p^{s_1}+a_2p^{s_2})q}\mathcal{E}_{s_1}(a,\Theta^*)[D_{a_1s_1},D_{a_2s_2}]$$

have the same field of definition.

We can use this relation to find the minimal ideal I in $\mathcal{B}$ such that $X\bmod I_{K_1(p)}$ is defined over an extension of K_1 with upper ramification number less than $qv_0-r^*(q-1)$. Indeed, we know that $I\bmod\mathcal{J}^2=\mathcal{B}^{(v_0)}\bmod\mathcal{J}^2$ and therefore, we may always assume that $I\supset\mathcal{B}^{(v_0)}\mathcal{J}$. As before, we are also allowed to change the right hand side of (4.6) by any element of $\mathcal{B}\otimes\mathcal{J}_{\mathrm{m}_1}$. We may always assume that $I\supset\mathcal{B}(v)$ for any $v>v_0$, because I must contain all $\mathcal{B}^{(v)}$ with $v>v_0$ and, by the inductive assumption, $\mathcal{B}^{(v)}$ coincides with $\mathcal{B}(v)$. So, we can assume that I contains the ideal $\mathcal{B}^{(v_0+)}$ generated by $\mathcal{B}^{(v_0)}\mathcal{J}$ and all $\mathcal{B}^{(v)}$ with $v>v_0$.

4.7. Final simplification of (4.6)**.** For $0 \leqslant s \leqslant M$, consider the identity $\mathcal{E}_s(a, \Theta^*) = p^s a t_1^{r^*(q-1)} + p^s t_1^{2r^*(q-1)} g_r(t_1)$ from Subsection 4.5.

Lemma 4.6. $p^s t_1^{-(a_1+a_2)p^s q + 2r^*(q-1)} D_{a_1 s} D_{a_2 s} \in \mathcal{B}_{K_1}^{(v_0)} \mathcal{J}_{K_1} + \mathcal{J}_{\mathrm{m}_1}$.

Proof. Indeed, if $p^s a_1 \geqslant v_0$ (resp. if $p^s a_2 \geqslant v_0$) then $p^s D_{a_1 s}$ (resp. $p^s D_{a_2 s}$) belongs to $\mathcal{B}_k^{(v_0)} \bmod \mathcal{J}_k^2$.

If both $p^s a_1, p^s a_2$ are less than v_0 then we use the fact that

$$-(a_1 + a_2)p^s q + 2r^*(q-1) > Cp^M + Cp^M > 0,$$

cf. Subsubsection 4.3.4, to conclude that the corresponding term belongs to $\mathcal{J}_{\mathrm{m}_1}$.

The lemma is proved □

The following lemma deals with the terms coming from the third sum and can be proved similarly.

Lemma 4.7. $p^{s_1} t_1^{-(p^{s_1} a_1 + p^{s_2} a_2)q + 2r^*(q-1)} [D_{a_1 s_1}, D_{a_2 s_2}] \in \mathcal{B}_{K_1}^{(v_0)} \mathcal{J}_{K_1} + \mathcal{J}_{\mathrm{m}_1}$.

The next lemma deals with the terms coming from the first sum.

Lemma 4.8. $p^s t_1^{-ap^s q + 2r^*(q-1)} D_{as} \in \mathcal{B}_{K_1}^{(v_0+)} + \mathcal{J}_{\mathrm{m}_1}$.

Proof. There is nothing to prove if $-ap^s q + 2r^*(q-1) > 0$.

Assume now that $ap^s q \geqslant 2r^*(q-1)$. Consider the expression for $\mathcal{F}_{ap^s}$, cf. Subsection 4.2. Notice that $ap^s > v_0$ (use estimate c) from n.4.3.4) and, therefore, $\mathcal{F}_{ap^s} \in \mathcal{B}_k(ap^s) = \mathcal{B}_k^{(ap^s)}$.

It will be sufficient to show that any term of degree 2 in the expression of $\mathcal{F}_{ap^s}$ belongs to $\mathcal{B}_k^{(v_0)} \mathcal{J}_k$. Indeed, it then follows that the linear term $p^s a D_{as}$ of $\mathcal{F}_{ap^s}$ belongs to $\mathcal{B}_k^{(ap^s)} + \mathcal{B}_k^{(v_0)} \mathcal{J}_k \subset \mathcal{B}_k^{(v_0+)}$ and the statement of our lemma is proved.

In order to prove this property of degree 2 terms notice that all of them contain as a factor either a product $p^{s_1} D_{a_1 s_1} D_{a_2 s_2}$ or a product $p^{s_1} D_{a_2 s_2} D_{a_1 s_1}$, where $s_1 \geqslant s_2$ and $p^{s_1} a_1 + p^{s_2} a_2 = p^s a$. Then we have the following two cases:

(1) if either $p^{s_1} a_1 \geqslant v_0$ or $p^{s_1} a_2 \geqslant v_0$ then this product belongs to $\mathcal{B}_k^{(v_0)} \mathcal{J}_k$;

(2) if both $p^{s_1} a_1$ and $p^{s_1} a_2$ are less than v_0, then $p^{s_1} a_1 < v_0 - \delta_1$ and $p^{s_2} a_2 \leqslant p^{s_1} a_2 < v_0 - \delta_1$. Therefore,

$$2r^*(q-1) \leqslant p^s a q = (p^{s_1} a_1 + p^{s_2} a_2) q < 2q(v_0 - \delta_1).$$

This contradicts the assumption a) from Subsubsection 4.3.4.

The lemma is completely proved. □

By the above three lemmas, we can everywhere replace the factors $\mathcal{E}_s(a,\Theta^*)$ by $p^s a t_1^{r^*(q-1)}$ and, therefore, the right hand side of (4.6) is congruent modulo $\mathcal{B}_{K_1}^{(v_0+)}+\mathcal{J}_{\mathrm{m}_1}$ to the sum $\sum_{\gamma\geqslant 0} t_1^{-q\gamma+r^*(q-1)}\mathcal{F}'_\gamma$, where $\mathcal{F}'_\gamma$ is given by the same formula as $\mathcal{F}_\gamma$, cf. Subsection 4.2, but with the additional restriction $n_2>M-N^*$ in the last sum.

Lemma 4.9. *If $\gamma\geqslant v_0$ then $\mathcal{F}'_\gamma\equiv\mathcal{F}_\gamma \operatorname{mod}\mathcal{B}_k^{(v_0)}\mathcal{J}_k$.*

Proof. Suppose the term $p^{n_1}a_1[D_{a_1n_1},D_{a_2n_2}]$ enters into the formula for $\mathcal{F}_\gamma$ but does not enter into the formula for $\mathcal{F}'_\gamma$.

Then $a_1,a_2\leqslant C$, $p^{n_1}a_1+p^{n_2}a_2=\gamma\geqslant v_0$ and $n_2\leqslant M-N^*$. Then

$$p^{n_1}a_1=\gamma-p^{n_2}a_2\geqslant v_0-p^Mq^{-1}C>r^*(1-q^{-1})-p^Mq^{-1}C>v_0-\delta_1$$

(use 4.3.2 a)). Therefore, $p^{n_1}a_1\geqslant v_0$, $p^{n_1}D_{a_1n_1}\in\mathcal{B}_k^{(v_0)}\mathcal{J}_k^2$ and $p^{n_1}a_1[D_{a_1n_1},D_{a_2n_2}]\in\mathcal{B}_k^{(v_0)}\mathcal{J}_k$.

The lemma is proved. ☐

Now notice that:

- if $\gamma>v_0$, then the term $t_1^{-q\gamma+r^*(q-1)}\mathcal{F}_\gamma$ belongs to $\mathcal{B}_{K_1}(\gamma)=\mathcal{B}_{K_1}^{(\gamma)}$;
- if $\gamma<v_0$, then the term $t_1^{-q\gamma+r^*(q-1)}\mathcal{F}'_\gamma$ belongs to $\mathcal{J}_{\mathrm{m}_1}$.

So, the ideal $\mathcal{B}^{(v_0)}$ appears as the minimal ideal I of $\mathcal{B}$ such that I contains the ideal $\mathcal{B}^{(v_0+)}$ and such that the largest upper ramification number of the field of definition over K_1 of the solution $X''\in\mathcal{B}_{K_1(p)}\operatorname{mod}I_{K_1(p)}$ of the equation

$$X''-\sigma X''=\mathcal{F}_{v_0}t_1^{-qv_0+r^*(q-1)}\operatorname{mod}I_{K_1(p)}$$

is less than $qv_0-r^*(q-1)$.

It only remains to notice that $p\mathcal{F}_{v_0}\in\mathcal{B}_k^{(v_0+)}$, and if $\mathcal{F}_{v_0}\notin I_k$ then the upper ramification number of the field of definition $K_1(X'',I)$ over K_1 is equal to $qv_0-r^*(q-1)$.

The theorem is proved.

5. Compatibility with ramification filtration

In this section with the notation from Section 1, $A=\mathcal{A}\operatorname{mod}\mathcal{J}^3$, $A_k=A\otimes W(k)$. For any $v\geqslant 0$, $A^{(v)}=\mathcal{A}^{(v)}\operatorname{mod}\mathcal{J}^3$, $A_k^{(v)}:=A^{(v)}\otimes W(k)$. We also set $J=\mathcal{J}\operatorname{mod}\mathcal{J}^3$ with the corresponding extension of scalars $J_k=J\otimes W(k)$. Suppose f is a continuous automorphism of the $\mathbb{Z}_p$-algebra A such that, for any $v\geqslant 0$, $f(A^{(v)})=A^{(v)}$. Consider the identification $\mathcal{J}\operatorname{mod}\mathcal{J}^2=\Gamma(p)^{\mathrm{ab}}$ from part b) of proposition 1.2 and denote again by f the continuous automorphism of $\mathcal{M}=I(p)^{\mathrm{ab}}\operatorname{mod}p$ induced by f. Consider the standard topological generators D_{an}, $a \in \mathbb{Z}(p), n \in \mathbb{Z} \bmod N_0$, for $\mathcal{M}$ and set, for any $a \in \mathbb{Z}(p)$,

$$f(D_{a0}) = \sum_{b,m} \alpha_{abm}(f) D_{bm},$$

where the coefficients $\alpha_{abm}(f) \in k$. With the above notation, the principal results of this section are:

if $\alpha_{110}(f) \neq 0$ and $N_0 \geqslant 3$ then

- there is an $\eta \in \mathrm{Aut}^0 K$ such that for any $a, b \in \mathbb{Z}(p)$ and $a \leqslant b < p^{N_0-3}$, it holds $\alpha_{ab0}(f) = \alpha_{ab0}(\eta^*)$;

- if $a \leqslant b < p^{N_0-3}$ and $m \in \mathbb{N}$ is such that $b/p^m < a$ then $\alpha_{a,b,-m \bmod N_0}(f) = 0$.

5.1. The elements $\mathcal{F}_\gamma(v)$. By Theorem B, cf. Subsection 4.2, for any $v \geqslant 0$, the ideal $A_k^{(v)}$ is the minimal closed σ-invariant ideal in A_k containing the explicitly given elements $\mathcal{F}_\gamma$, for all $\gamma \geqslant v$. For any $a \in \mathbb{Z}(p)$ and $n \in \mathbb{Z} \bmod N_0$, set $\Delta_{a0} = (1/a)\mathcal{F}_a$ and $\Delta_{an} = \sigma^n \Delta_{a0}$. Then $\Delta_{an} \equiv D_{an} \bmod \mathcal{J}_k^2$ and $\{\Delta_{an} \mid a \in \mathbb{Z}(p), n \in \mathbb{Z} \bmod N_0\} \cup \{D_0\}$ is a new system of topological generators for A_k. The elements of this new set of generators together with their pairwise products form a topological basis of the $W(k)$-module A_k.

For any $\gamma \geqslant v \geqslant 0$, consider the following elements $\mathcal{F}_\gamma(v)$ (these elements have already been mentioned in Subsection 4.2):

If $\gamma = ap^m$ with $a \in \mathbb{Z}(p)$ and $m \in \mathbb{Z}_{\geqslant 0}$ set

$$\mathcal{F}_\gamma(v) = p^m a \Delta_{am} - \sum_{\substack{n \geqslant 0, a_1, a_2 \in \mathbb{Z}(p) \\ p^n(a_1+a_2)=\gamma \\ p^n a_1, p^n a_2 < v}} p^n a_1 \Delta_{a_1 n} \Delta_{a_2 n};$$

If $\gamma \notin \mathbb{Z}$ set

$$\mathcal{F}_\gamma(v) = - \sum_{\substack{n_1 \geqslant 0, a_1, a_2 \in \mathbb{Z}(p) \\ p^{n_1} a_1 + p^{n_2} a_2 = \gamma \\ p^{n_1} a_1, p^{n_1} a_2 < v}} p^{n_1} a_1 [\Delta_{a_1 n_1}, \Delta_{a_2 n_2}].$$

Similarly to Subsection 4.2, we have the following property.

Proposition 5.1. *For any $v \geqslant 0$, $A_k^{(v)}$ is the minimal σ-invariant closed ideal of A_k containing the elements $\mathcal{F}_\gamma(v)$ for all $\gamma \geqslant v$.*

5.2. The submodules $A_{\mathrm{tr}}^{(v)}$ and $A_{\mathrm{adm}}^{(v)}$. Suppose $v\geqslant 0$.

Let $A_{\mathrm{tr}}^{(v)}$ be the $W(k)$-submodule in A_k generated by the following elements:

tr$_1$) $p^s\Delta_{an}$ with $s\geqslant 0$ and $p^sa\geqslant 2v$;

tr$_2$) $p^s\Delta_{a_1n_1}\Delta_{a_2n_2}$ with $a_1,a_2\in\mathbb{Z}(p)$, $s\geqslant 0$ and $n_1,n_2\in\mathbb{Z}\operatorname{mod}N_0$ such that $\max\{p^sa_1,p^sa_2\}\geqslant v$.

Let $A_{\mathrm{adm}}^{(v)}$ be the minimal closed $W(k)$-submodule in A_k containing $A_{\mathrm{tr}}^{(v)}$ and the following elements:

adm$_1$) $p^s\Delta_{an}$, with $s\geqslant 0$, $a\in\mathbb{Z}(p)$ and $p^sa\geqslant v$;

adm$_2$) $p^s\Delta_{a_1n_1}\Delta_{a_2n_2}$, where $a_1,a_2\in\mathbb{Z}(p)$, $n_1,n_2\in\mathbb{Z}\operatorname{mod}N_0$ and $s=s(a_1,a_2)\in\mathbb{Z}_{\geqslant 0}$ are such that:

(1) $v/p\leqslant\max\{p^sa_1,p^sa_2\}<v$;

(2) $\max\left\{p^s\left(a_1+\frac{a_2}{p^{n_{12}}}\right),p^s\left(\frac{a_1}{p^{n_{21}}}+a_2\right)\right\}\geqslant v$, where $0\leqslant n_{12},n_{21}<N_0$, $n_{12}\equiv n_1-n_2\operatorname{mod}N_0$ and $n_{21}\equiv n_2-n_1\operatorname{mod}N_0$;

(3) if $n_1=n_2$ then $a_1+a_2\equiv 0\operatorname{mod}p$.

Proposition 5.2. *For any $v\geqslant 0$,*
1) $f(A_{\mathrm{tr}}^{(v)})=A_{\mathrm{tr}}^{(v)}$*;*
2) $A_{\mathrm{adm}}^{(v)}\supset A_k^{(v)}\supset A_{\mathrm{tr}}^{(v)}\supset pA_{\mathrm{adm}}^{(v)}$*;*
3) *the elements from* adm$_1$) *and* adm$_2$) *form a k-basis of* $A_{\mathrm{adm}}^{(v)}\operatorname{mod}A_{\mathrm{tr}}^{(v)}$*.*

Proof. 1) It is sufficient to notice that $A_{\mathrm{tr}}^{(v)}$ is the minimal σ-invariant $W(k)$-submodule in A containing $\sum_{\gamma\geqslant 2v}\mathcal{F}_\gamma(v)W(k)+\sum_{\gamma\geqslant v}\mathcal{F}_\gamma(v)J_k$.

2) From the above n.1) it follows that $A_k^{(v)}\supset A_{\mathrm{tr}}^{(v)}$. The embedding $A_k^{(v)}\subset A_{\mathrm{adm}}^{(v)}$ follows from the definition of $A_{\mathrm{adm}}^{(v)}$: as a matter of fact, $A_{\mathrm{tr}}^{(v)}$ is spanned by all summands of elements $\sigma^s\mathcal{F}_\gamma$ with $s\in\mathbb{Z}\operatorname{mod}N_0$ and $\gamma\geqslant v$. The embedding $pA_{\mathrm{adm}}^{(v)}\subset A_{\mathrm{tr}}^{(v)}$ follows from the fact that each element listed in adm$_1$) and adm$_2$) belongs to $A_{\mathrm{tr}}^{(v)}$ after multiplication by p.

3) It is easy to see that any k-linear combination of the elements from adm$_1$) and adm$_2$) does not belong to $A_{\mathrm{tr}}^{(v)}\operatorname{mod}pA_{\mathrm{adm}}^{(v)}$. □

Proposition 5.3. *Suppose $v\geqslant 0$ and $p^s\Delta_{a_1n_1}\Delta_{a_2n_2}$ is one of elements listed in* adm$_2$)*. Let $n=\min\{n_{12},n_{21}\}$. If*

$$v/p^{N_0-n}\leqslant d(v):=\min\{v-a\mid a\in\mathbb{Z},a<v\}$$

then there are unique $m\in\mathbb{Z}\operatorname{mod}N_0$ and $\gamma\geqslant v$ such that $p^sa_1\Delta_{a_1n_1}\Delta_{a_2n_2}$ appears (with non-zero coefficient) in the expression of $\sigma^m\mathcal{F}_\gamma(v)$.

Remark. We are going to apply this proposition in the following situations:

(1) $v \in \mathbb{N}$, $v < p^{N_0}$, $n_1 = n_2 = 0$;

(2) $v = c + 1/p$, $n_1 = 0$, $n_2 = -1$, where $c \in \mathbb{N}$ and $c < p^{N_0-2}$.

Proof. By symmetry we may assume that $n = n_{12}$.

If $n_{12} \neq 0$ we have $p^s\left(a_1 + \frac{a_2}{p^n}\right) = \gamma \geqslant v$, because of property adm$_2$)(2), and

$$p^s\left(\frac{a_1}{p^{N_0-n}} + a_2\right) < \frac{v}{p^{N_0-n}} + p^s a_2 \leqslant d(v) + (v - d(v)) = v \leqslant \gamma.$$

Therefore, the term $p^s\Delta_{a_1n_1}\Delta_{a_2n_2}$ appears in the expression of $\sigma^{n_1-s}\mathcal{F}_\gamma(v)$. This term will appear in the expression of another $\sigma^{n'}\mathcal{F}_{\gamma'}(v)$, where $\gamma' \geqslant v$, if and only if $p^s\left(a_1 + \frac{a_2}{p^{n+mN_0}}\right) \geqslant v$ or $p^s\left(\frac{a_1}{p^{mN_0-n}} + a_2\right) \geqslant v$, where $m \in \mathbb{N}$. But the condition $v/p^{N_0-n} < d(v)$ implies that all such numbers are less than v.

If $n_{12} = 0$ then $\gamma = p^s(a_1 + a_2) \geqslant v$ and $p^s\Delta_{a_1n_1}\Delta_{a_2n_2}$ appears in the expression of $\sigma^{n_1-s}\mathcal{F}_\gamma(v)$. This element can appear in the expression of another $\sigma^{n'}\mathcal{F}_{\gamma'}(v)$, where $\gamma' \geqslant v$, if and only if $\gamma' = p^s\left(a_1 + \frac{a_2}{p^{mN_0}}\right) \geqslant v$ or $\gamma' = p^s\left(\frac{a_1}{p^{mN_0}} + a_2\right) \geqslant v$, where $m \in \mathbb{N}$. As earlier, $\gamma' < v$ in both cases.

The proposition is proved. ☐

Remark. If $v/p^{N_0/2} < d(v)$, then elements of the set

$$\{\sigma^s\mathcal{F}_\gamma^{(v)} \bmod A_{\mathrm{adm}}^{(v)} \mid 0 \leqslant s < N_0, \gamma \geqslant v\}$$

are linear combinations of disjoint groups of elements listed in adm$_1$) and adm$_2$).

5.3. Denote by the same symbol f the morphism of $W(k)$-modules

$$A^{(v)} \bmod A_{\mathrm{tr}}^{(v)} \longrightarrow A^{(v)} \bmod A_{\mathrm{tr}}^{(v)},$$

which is induced by $f : A \longrightarrow A$. As earlier, denote again by f the k-linear extension of the automorphism of $\mathcal{M}$, which is induced by f. Because the images of D_{an} and Δ_{an} coincide in $\mathcal{M}_k$, we have, for any $a \in \mathbb{Z}(p)$,

$$f(\Delta_{a0}) = \sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z} \bmod N_0}} \alpha_{abm}(f)\Delta_{bm}.$$

It will be convenient sometimes to set $\alpha_{ab0}(f) = 0$ if a or b are divisible by p.

Proposition 5.4. *Suppose $\alpha_{110}(f) = \alpha \in k^*$. Then $\alpha_{aa0}(f) = \alpha^a$, for any $a \in \mathbb{Z}(p)$ such that $a < p^{N_0-1}$ if $p \neq 2$ and $N_0 \geqslant 2$, and such that $a < 2^{N_0}$ if $p = 2$ and $N_0 \geqslant 3$.*

Proof. By proposition 5.3, for any $v \leqslant p^{N_0}$ such that $v \equiv 0 \bmod p$, the formula for $f(\mathcal{F}_v(v)) \bmod A_{\mathrm{tr}}^{(v)}$ must contain all terms $a_1\Delta_{a_10}\Delta_{a_20}$, for which $a_1 + a_2 = v$, and the term $p^s a\Delta_{as}$, where $p^s a = v$ and $a \in \mathbb{Z}(p)$, with the same coefficient. In other words, for such indices $a_1, a_2, a \in \mathbb{Z}(p)$,

$$\alpha_{a_1a_10}(f)\alpha_{a_2a_20}(f) = \sigma^s\alpha_{aa0}(f). \tag{5.1}$$

For $a \in \mathbb{Z}(p)$, $a < p^{N_0}$, set $\gamma(a) = \alpha_{aa0}(f)\alpha_{110}(f)^{-1}$. Then $\gamma(1) = 1$ and $\gamma(a_1)\gamma(a_2) = \gamma(a)^{p^s}$ if $a_1 + a_2 = p^s a$.

Suppose $p \neq 2$.

First, we prove that for $n \in \mathbb{Z}(p)$ satisfying $1 \leqslant n < p^{N_0-1}$, we have

$$\gamma(n) = \gamma(2)^{n-1}. \tag{5.2}$$

This is obviously true for $n = 1$ and $n = 2$.

Assume that $n \geqslant 2$ and that $\gamma(m) = \gamma(2)^{m-1}$ holds for all $m \in \mathbb{Z}(p)$ such that $m \leqslant n$. Consider a special case of relation (5.1) with $n \in \mathbb{Z}(p)$

$$\gamma(1)\gamma(np-1) = \gamma(n)^p. \tag{5.3}$$

If $n \not\equiv -1 \bmod p$ then use the relation $\gamma(p-1)\gamma(p+1) = \gamma(2)^p$, which is again a special case of (5.1), to deduce from (5.3) that

$$\gamma(n+1) = \gamma(1)\gamma(n+1) = \gamma(n)\gamma(2) = \gamma(2)^n.$$

If $n \equiv -1 \bmod p$ and $p \neq 3$ then $n \geqslant 4$ and by the inductive assumption $\gamma(3) = \gamma(2)^2$. Apply the relation $\gamma(p-1)\gamma(2p+1) = \gamma(3)^p = \gamma(2)^{2p}$ to deduce from (5.3) that

$$\gamma(n+1) = \gamma(1)\gamma(n+2) = \gamma(n)\gamma(2)^2 = \gamma(2)^{n+1}.$$

If $p = 3$ then $\gamma(p-1)\gamma(2p+1) = \gamma(1)^{p^2}$ and we obtain from (5.3) that

$$\gamma(n+1) = \gamma(1)\gamma(n+2) = \gamma(n) = \gamma(2)^{n-1} = \gamma(2)^{n+1},$$

because $\gamma(2) = 1$ (using that $\gamma(1)\gamma(2) = \gamma(1)^3$).

So, relation (5.2) is proved.

Still assuming that $p \neq 2$ prove that $\gamma(2) = 1$. The relation $\gamma(1)\gamma(p-1) = \gamma(1)^p$ implies that $\gamma(2)^{p-2} = \gamma(p-1) = 1$. The equality $\gamma(1)\gamma(p^2-1) = \gamma(1)^{p^2}$ implies that $\gamma(2)^{p^2-2} = \gamma(p^2-1) = 1$. Then $\gamma(2) = 1$ because $p^2 - 2$ and $p - 2$ are coprime. This completes the case $p \neq 2$.

Consider now the case $p = 2$.

Notice that for any $n \in \mathbb{Z}(2)$ such that $1 < n < 2^{N_0}$, we have $n+1 = 2^s a$, where $a \in \mathbb{Z}(2)$, $s \in \mathbb{N}$ and $a < n$. Therefore, $\gamma(1)\gamma(n) = \gamma(a)^{2^s}$ and the equality $\gamma(n) = 1$ follows by induction on $n \geqslant 1$ for all $n < 2^{N_0}$. □

Corollary 5.5. *If $\alpha_{110}(f) = 1$ then $\alpha_{aa0}(f) = 1$ whenever $a < p^{N_0-1}$, $p \neq 2$ or $a < 2^{N_0}$, $p = 2$.*

Proposition 5.6. *Suppose $N_0 \geqslant 3$, $\alpha_{110}(f) \in k^*$, $a, b \in \mathbb{Z}(p)$, $a, b < p^{N_0-2}$. If $0 \leqslant m < N_0$ and $b/p^m < a$ then $\alpha_{a,b,-m \bmod N_0}(f) = 0$.*

Proof. For a given $b\in\mathbb{Z}(p)$, $b<p^{N_0-2}$ and $1\leqslant m<N_0$, let $a\in\mathbb{Z}(p)$ be the minimal integer such that $\alpha_{a',b,-m}(f)=0$ if $a'>a$. If such an a does not exist then $\alpha_{a,b,-m}(f)=0$ for all a and there is nothing to prove.

If $p\neq 2$ put $v=p^{N_0-1}$ and consider $f(\mathcal{F}_v(v)) \operatorname{mod}(A^{(v)}_{\mathrm{tr}}+pA^{(v)}_{\mathrm{adm}})$.

We prove that the term $\Delta_{v-a,0}\Delta_{b,-m}$ enters in $f(\mathcal{F}_v(v))$ with the coefficient

$$(v-a)\alpha_{v-a,v-a,0}(f)\alpha_{a,b,-m}(f)=-a\alpha_{v-a,v-a,0}(f)\alpha_{a,b,-m}(f). \tag{5.4}$$

Indeed, $\mathcal{F}_v(v)\operatorname{mod}(A^{(v)}_{\mathrm{tr}}+pA^{(v)}_{\mathrm{adm}})$ is a sum of the terms of the form $a_1\Delta_{a_10}\Delta_{a_20}$ with $a_1,a_2\in\mathbb{Z}(p)$ such that $a_1+a_2=v$. Therefore, $f(a_1\Delta_{a_10}\Delta_{a_20})$ contains $\Delta_{v-a,0}\Delta_{b,-m}$ with coefficient

$$a_1\alpha_{a_1,v-a,0}(f)\alpha_{a_2,b,-m}(f).$$

Now notice that $\alpha_{a_2,b,-m}(f)=0$ if $a_2>a$, and $\alpha_{a_1,v-a,0}(f)=0$ if $a_1>v-a$ or, equivalently, if $a_2<a$. So, $a_1=v-a$ and the coefficient is given by formula (5.4).

By the choice of a, the coefficient (5.4) is not zero. Therefore, $\Delta_{v-a,0}\Delta_{b,-m}\in A^{(v)}_{\mathrm{adm}}$. Notice that

$$\max\left\{v-a+\frac{b}{p^m},\frac{v-a}{p^{N_0-m}}+b\right\}=v-a+\frac{b}{p^m}$$

and $b/p^m\geqslant a$. Indeed, we can use that

$$\frac{v-a}{p^{N_0-m}}+b<\frac{p^{N_0-1}}{p}+p^{N_0-2}<2p^{N_0-2}<p^{N_0-1}-p^{N_0-2}<v-a+\frac{b}{p^m}.$$

Therefore, $v-a+b/p^m\geqslant v$, i.e. $b/p^m\geqslant a$ and the proposition is proved in the case $p\neq 2$.

If $p=2$ we can take $v=2^{N_0}$ and repeat the above arguments by using in the last step the inequality

$$\frac{v-a}{2^{N_0-m}}+b<\frac{2^{N_0}}{2}+2^{N_0-2}<2^{N_0}-a\left(1-\frac{1}{2^m}\right)\leqslant v-a+\frac{b}{2^m}.$$

The proposition is completely proved. □

5.4. Suppose $r\in\mathbb{N}$ is such that $\alpha_{aa'0}(f)=0$ for any $a,a'\in\mathbb{Z}(p)$ such that $a<a'<a+r<p^{N_0-2}$.

Let $\delta(p)$ be p if $p\neq 2$ and $\delta(p)=4$ if $p=2$.

Proposition 5.7. *Assume that $\alpha_{110}(f)=1$. If $b,b_1\in\mathbb{Z}(p)$, $b_1=b+r$ and $b_1+\delta(p)<p^{N_0-2}$ then $\alpha_{bb_10}(f)=\alpha_{b-\delta(p),b_1-\delta(p),0}(f)$.*

Proof. Let $a_0=p^{N_0-2}-1$, $v_0=a_0+1/p$, $v=a_0+\frac{b}{p}$. We need the following lemma.

Lemma 5.8. *If $a',b',c\leqslant a_0$ and $a'+b'/p=v$ then $\alpha_{a',c,-1}(f)=0$.*

Proof. It follows from the inequalities

$$\frac{c}{p} \leqslant \frac{a_0}{p} \leqslant a_0 - \frac{a_0}{p} < v - \frac{b'}{p} = a'$$

and proposition 5.6. □

We continue the proof of proposition 5.7. Consider

$$\mathcal{F}_v(v_0) = -\sum_{\substack{a'+b'/p=v\\ a',b'\leqslant a_0}} a'[\Delta_{a'0}, \Delta_{b',-1}] \bmod pA^{(v)}_{\mathrm{adm}}.$$

Using that $v_0/p^{N_0-1} < d(v_0) = 1/p$, cf. proposition 5.3, we can find now the coefficient for $[\Delta_{a_00}, \Delta_{b_1,-1}]$ in $f(\mathcal{F}_v(v_0))$. By the above lemma $\alpha_{a',b,-1}(f) = 0$, therefore the image of the term $a'[\Delta_{a'0}, \Delta_{b',-1}]$ gives a coefficient

$$a'\alpha_{a'a_00}(f)\sigma^{-1}(\alpha_{b'b_10}(f)).$$

If $a' < a_0$ and $\alpha_{a'a_00}(f) \neq 0$ then $a' \leqslant a_0 - r$, $b' \geqslant b + rp > b_1$ and $\alpha_{b'b_10}(f) = 0$. So, the coefficient is non-zero only for $a' = a_0$. Then by Corollary 5.5 $\alpha_{a'a_00}(f) = 1$ and the coefficient will be equal to $a_0\sigma^{-1}(\alpha_{bb_10}(f))$.

If $p \neq 2$ we can proceed similarly to find the coefficient for $[\Delta_{a_0-1,0}, \Delta_{b_1+p,-1}]$ in $f(\mathcal{F}_v(v_0))$. It equals $(a_0 - 1)\sigma^{-1}(\alpha_{b+p,b_1+p,0}(f))$. Therefore, by proposition 5.3

$$\alpha_{bb_10}(f) = \alpha_{b+p,b_1+p,0}(f)$$

and the case $p \neq 2$ is completely considered.

If $p = 2$, we similarly find similarly the coefficient for $[\Delta_{a_0-2,0}, \Delta_{b_1+4,-1}]$ in $f(\mathcal{F}_v(v_0))$. It equals $(a_0 - 2)\sigma^{-1}(\alpha_{b+4,b_1+4,0}(f))$ and we obtain

$$\alpha_{bb_10}(f) = \alpha_{b+4,b_1+4,0}(f).$$

The proposition is proved. □

5.5. Now we come to the central point of this section.

Proposition 5.9. *Suppose $\alpha_{110}(f) \neq 0$ and $N_0 \geqslant 3$. Then there is an $\eta \in \mathrm{Aut}^0 K$ such that $\alpha_{ab0}(f\eta^*) = \delta_{ab}$, for any $a, b \in \mathbb{Z}(p)$ with $a \leqslant b < p^{N_0-3}$, where δ_{ab} is the Kronecker symbol.*

Proof. Proposition 5.4 together with part 2) of proposition 2.1 imply that after replacing f by $f\eta^*$ for some $\eta \in \mathrm{Aut}^0 K$ such that $\eta(t) = \alpha_{110}(f)t$, we can assume that $\alpha_{aa0}(f) = 1$ if $a < p^{N_0-1}$.

Let $r = r(f) \in \mathbb{N}$ be the maximal subject to the condition that $\alpha_{ab0}(f) = 0$, for any $a, b \in \mathbb{Z}(p)$ with $a, b < p^{N_0-2}$ and $a < b < a + r$.

If $r \geqslant p^{N_0-3} - 1$ then there is nothing to prove. Therefore, we can assume that $r \leqslant p^{N_0-3} - 2$. For $1 \leqslant a < p^{N_0-2}$, set $\alpha_a(r) = \alpha_{a,a+r,0}(f)$ if $a \in \mathbb{Z}(p)$ and $\alpha_a(r) = 0$, otherwise.

By proposition 5.7 $\alpha_a(r)$ depends only on the residue $a \bmod \delta(p)$ and by the choice of r the function $a \mapsto \alpha_a(r)$ is not identically zero. The proposition will be proved if we show the existence of $\eta \in \mathrm{Aut}^0 K$ such that $r(f\eta^*) > r(f)$.

In the case $p \neq 2$ apply proposition 2.5 with $w_0 = 1+r$. Let η will be the corresponding character. If $r(f\eta^*) > r(f)$, then the proposition is proved. So, assume that $r(f\eta^*) = r(f)$. Therefore, by replacing f by $f\eta^*$ we can assume the following normalisation conditions:

a) $\alpha_1(r) = 0$ if $r \not\equiv -1 \bmod p$;

b) $\alpha_2(r) = 0$ if $r \equiv -1 \bmod p$.

In the case $p = 2$, apply proposition 2.6 with either $w_0 = r + 2$ if $r \equiv 2 \bmod 4$ or $w_0 = r$ if $r \equiv 0 \bmod 4$. In the first case we have the normalisation condition

c) $\alpha_1(r) = \alpha_3(r) = 0$;

in the second case we obtain only that

d) $\alpha_1(r) = 0$.

The case $p \neq 2$.

If $r = p^{N_0-3} - 2$ then $\alpha_1(r) = \alpha_{ab0}(f) = 0$ if $a = 1, b = p^{N_0-3} - 1$. For all other couples $a, b \in \mathbb{Z}(p)$ such that $a < b < p^{N_0-3}$, we have $\alpha_{ab0}(f) = 0$ because $b - a < r$. Therefore, we can assume that $r \leqslant p^{N_0-3} - 3$.

Let $c_j = p(r+1)+j$ for $j = 1, 2, \dots, p-1$. Then $c_j \leqslant p(p^{N_0-3}-2)+p-1 < p^{N_0-2}$, for all j. Set $v_j = c_j + 1/p$ and consider the coefficient for $\mathcal{F}_{v_j+r}(v_j)$ in the image $f(\mathcal{F}_{v_j}(v_j)) \in A^{(v_j)}_{\mathrm{adm}} \bmod A^{(v_j)}_{\mathrm{tr}} + pA^{(v_j)}_{\mathrm{adm}}$.

Similarly to the proof of proposition 5.7, we see that the term $[\Delta_{c_j0}, \Delta_{1+rp,-1}]$ from the expression of $\mathcal{F}_{v_j+r}(v_j)$ can appear with non-zero coefficient only as image of one of the following two terms from $\mathcal{F}_{v_j}(v_j)$: $(c_j - r)[\Delta_{c_j-r,0}, \Delta_{1+rp,-1}]$ and $c_j[\Delta_{c_j0}, \Delta_{1,-1}]$. This coefficient is equal to

$$(c_j - r)\alpha_{c_j-r}(r) + c_j\alpha_{1,1+rp,0}(f).$$

Similarly, the term $[\Delta_{c_j-1,0}, \Delta_{1+(r+1)p,-1}]$ from the expression of $\mathcal{F}_{v_j+r}(v_j)$ can appear with non-zero coefficient only in the image of either $(c_j-1-r)[\Delta_{c_j-1-r,0}, \Delta_{1+(r+1)p,-1}]$ or $(c_j-1)[\Delta_{c_j-1,0}, \Delta_{1+p,-1}]$. Therefore, this coefficient will be equal to

$$(c_j - 1 - r)\alpha_{c_j-1-r}(r) + (c_j - 1)\sigma^{-1}\alpha_{1+p,1+(r+1)p,0}(f)$$

and we obtain the following relation

$$\frac{c_j - r}{c_j}\alpha_{c_j-r}(r) = \frac{c_j - 1 - r}{c_j - 1}\alpha_{c_j-1-r}(r) + X, \tag{5.5}$$

where $X = \sigma^{-1}(\alpha_{1+p,1+(r+1)p,0}(f)) - \sigma^{-1}(\alpha_{1,1+rp,0}(f))$.

For $j = 1, \dots, p-1$, set $\beta_j = \frac{c_j - r}{c_j}\alpha_{j-r}(r)$. Then the above relation (5.5) implies that $\beta_2 = \beta_1 + X, \beta_3 = \beta_2 + X, \dots, \beta_{p-1} = \beta_{p-2} + X$.

The case $r \not\equiv 0 \bmod p$, $p \neq 2$.

In this case the normalisation conditions imply that

— if $r \not\equiv -1 \bmod p$ then $\beta_{r+1} = 0$;

— if $r \equiv -1 \bmod p$ then $\beta_{r+2} = 0$.

In both cases $\beta_r = 0$. This implies that $\beta_1 = \dots = \beta_{p-1} = 0$. Therefore, $\alpha_a(r) = 0$, for all a. This is a contradiction.

So, in the case $r \not\equiv 0 \bmod p$, $p \neq 2$ the proposition is proved.

The case $r \equiv 0 \bmod p$, $p \neq 2$

In this case we only have the normalisation condition $\beta_1 = 0$. Therefore, for $i = 1, \dots, p-1$, we have $\beta_i = (i-1)X$ and $\alpha_a(r) = (a-1)X$ for any $a \in \mathbb{Z}(p)$, $a < p^{N_0 - 3}$.

Let $v = (p-1)r + p$ and consider the coefficient for $\mathcal{F}_{v+r}(v)$ in the image $f(\mathcal{F}_v(v))$. Following the images of terms of degree 2 we see that this coefficient equals $-2X$. Now notice that the linear terms in $\mathcal{F}_v(v)$ (resp. $\mathcal{F}_{v+r}(v)$) have coefficients with p-adic valuation $v_p((p-1)r+p)$ (resp. $v_p(pr+p)$). Clearly, if $1 = v_p(pr+p)$ and if $1 < v_p((p-1)r+p)$ then the linear term of $\mathcal{F}_{v+r}(v)$ cannot appear in the image $f(\mathcal{F}_v(v))$. Therefore, $1 = v_p(pr+p) = v_p((p-1)r+p)$ and the linear terms in $\mathcal{F}_v(v)$ (resp. $\mathcal{F}_{v+r}(v)$) are multiples of $\Delta_{r+1-r/p,1}$ (resp. $\Delta_{r+1,1}$). But then $(r+1) - (r + 1 - r/p) = r/p < r$ and by the definition of r, $\Delta_{r+1,1}$ will not appear in the image $F(\Delta_{r+1-r/p,1})$. This contradiction proves the proposition in the case $r \equiv 0 \bmod p$, $p \neq 2$.

The case $p = 2$.

Here $r \equiv 0 \bmod 2$. If $r \equiv 2 \bmod 4$ then the normalisation conditions imply that $\alpha_a(r) = 0$ for all a and the proposition is proved.

If $r \equiv 0 \bmod 4$ then we only have one normalisation condition $\alpha_a(r) = 0$ if $a \equiv 1 \bmod 4$. Let $\alpha_a(r) = \alpha$ where $a \equiv 3 \bmod 4$. Consider

$$\mathcal{F}_{r+4}(r+4) = (r+4)\Delta_{\frac{r+4}{2^s},s} + \sum_{a+b=r+4a,b<r+4} \Delta_{a0}\Delta_{b0} \in A_{\mathrm{adm}}^{(r+4)} \bmod A_{\mathrm{tr}}^{(r+4)},$$

where $s = v_2(r+4) \geqslant 2$. Then $f(\mathcal{F}_{r+4}(r+4))$ contains $\Delta_{r+1,0}\Delta_{r+3,0}$ with coefficient

$$\alpha_{1,r+1,0}(f) + \alpha_{3,3+r,0}(f) = \alpha,$$

and therefore it contains $\mathcal{F}_{2r+4}(r+4)$ with coefficient α. Similarly to the case $p \neq 2$, we obtain the equality $v_2(r+4) = v_2(2r+4) = 2$ and consequently the fact that $f(\Delta_{r/2+1,2})$ cannot contain $\Delta_{r/4+1,2}$ with non-zero coefficient because $(r/2+1) - (r/4+1) = r/4 < r$. The proposition is completely proved. □

6. Proof of the main theorem — the characteristic p case

Suppose E is a field of characteristic p.

Then E' is also a field of characteristic p, because the topological groups $\Gamma_E(p)^{\mathrm{ab}}$ and $\Gamma_{E'}(p)^{\mathrm{ab}}$ are isomorphic. Looking at the ramification filtrations of these groups we deduce that the residue fields of E and E' are isomorphic. Therefore, E and E' are isomorphic complete discrete valuation fields and we can identify the maximal p-extensions $E(p)$ of E and $E'(p)$ of E'.

Let K be a finite Galois extension of E in $E(p)$. Then $E(p)$ is a maximal p-extension of K and $\Gamma_K(p)=\mathrm{Gal}(E(p)/K)$. Let K' be the extension of E' in $E(p)$ such that $g(\Gamma_K(p))=\Gamma_{K'}(p)$ (recall that g is a group isomorphism). If $s\geqslant 0$ and K_s is the unramified extension of K in $E(p)$ such that $[K_s:K]=p^s$ then $g(\Gamma_{K_s}(p))=\Gamma_{K'_s}(p)$, where K'_s is the unramified extension of K' in $E(p)$ of degree p^s. Therefore, with the notation from Section 3 we have a compatible system $g_{KK'}=\{g_{KK's}\}_{s\geqslant 0}$ of $\mathbb{F}_p$-linear continuous automorphisms $g_{KK's}:\bar{\mathcal{M}}_{Ks}\longrightarrow\bar{\mathcal{M}}_{K's}$.

Now choose uniformising elements t_K and $t_{K'}$ in K and, resp., K'. Consider the corresponding standard generators $D^{(s)}_{an}$ (resp. $D'^{(s)}_{an}$), where $a\in\mathbb{Z}(p)$ and $n\in\mathbb{Z}\,\mathrm{mod}\,N_s$, of $\bar{\mathcal{M}}_{Ks}=\mathcal{M}_{Ks}\hat{\otimes}_k k(p)$ (resp., $\bar{\mathcal{M}}_{K's}=\mathcal{M}_{Ks}\hat{\otimes}_k k(p)$). Here, as usual, $k\simeq\mathbb{F}_{q_0}$ is the residue field of K, $q_0=p^{N_0}$, $N_s=N_0p^s$. Then

$$g_{KK's}(D^{(s)}_{a0})=\sum_{\substack{b\in\mathbb{Z}(p)\\ m\in\mathbb{Z}\,\mathrm{mod}\,N_s}}\alpha_{abm}(g_{KK's})D'^{(s)}_{bm}$$

with $\alpha_{abm}(g_{KK's})\in k_s\subset k(p)$.

For each $s\geqslant 0$, choose $n_s\in\mathbb{Z}\,\mathrm{mod}\,N_s$ such that $\alpha_{11n_s}(g_{KK's})\neq 0$: n_s exists, because $g_{KK's}$ induces a $k(p)$-linear isomorphism of $\bar{\mathcal{M}}_{Ks}\,\mathrm{mod}\,\bar{\mathcal{M}}^{(2)}_{Ks}$ and $\bar{\mathcal{M}}_{K's}\,\mathrm{mod}\,\bar{\mathcal{M}}^{(2)}_{K's}$.

Let $\mathrm{Fr}(t_{K'})\in\mathrm{Aut}K'_{\mathrm{ur}}$ be such that $\mathrm{Fr}(t_{K'}):t_{K'}\mapsto t_{K'}$ and $\mathrm{Fr}(t_{K'})|_{k(p)}=\sigma$. Let $\xi\in\mathrm{Iso}^0(K'_{\mathrm{ur}},K_{\mathrm{ur}})$ be such that $\xi(t_{K'})=t_K$.

For any $s\geqslant 0$, $\mathrm{Fr}(t_{K'})$ (resp. ξ) induces a continuous field isomorphism $K'_s\longrightarrow K'_s$ (resp. $K'_s\longrightarrow K_s$). It will be denoted by $\mathrm{Fr}(t_{K'})_s$ (resp. ξ_s). With notation from n.3, we introduce continuous group isomorphisms

$$g^0_{KK's}=g_{KK's}\mathrm{Fr}(t_{K'})^{n_s*}_s:\bar{\mathcal{M}}_{Ks}\longrightarrow\bar{\mathcal{M}}_{K's}.$$

Clearly, $h_s:=g^0_{KK's}\xi^*_s$ is induced by an automorphism of $\Gamma_{K_s}(p)$ which is compatible with the ramification filtration. Notice also that, by proposition 2.1, if $a\in\mathbb{Z}(p)$, $n\in\mathbb{Z}\,\mathrm{mod}\,N_s$ and

$$h_s(D^{(s)}_{a0})=\sum_{b,m}\alpha_{abm}(h_s)D^{(s)}_{bm},$$

then $\alpha_{a,b,m-n_s}(h_s) = \sigma^{n_s}\alpha_{abm}(g_{KK's})$. In particular, $\alpha_{110}(h_s) \neq 0$. Therefore, applying proposition 5.6, we obtain that for all $s \geqslant 0$,

$$h_s \in \mathrm{Aut}_{\mathrm{adm}}\mathcal{M}_{Ks} \bmod \mathcal{M}_{K_s}^{(p^{N_s-2})},$$

the residues $n_s \in \mathbb{Z} \bmod N_s$ are unique, and $n_{s+1} \bmod N_s = n_s$. Here we use that $D_{an}^{(s+1)} \mapsto D_{an}^{(s)}$ under the natural morphism from $\bar{\mathcal{M}}_{K,s+1}$ to $\bar{\mathcal{M}}_{Ks}$. Then $h_{KK} := \{h_s\}_{s\geqslant 0}$ and $g^0_{KK'} := \{g^0_{KK's}\}_{s\geqslant 0}$ are compatible systems and, by propositions 3.3 and 5.9, they are special admisible locally analytic systems. By proposition 3.4 there is an $\eta_{KK'} \in \mathrm{Iso}^0(K, K')$ such that $g^0_{KK'\mathrm{an}} = \mathrm{d}(\eta_{KK'})\hat{\otimes}_k k(p)$. Notice also that if $\bar{n}_{KK'} := \varprojlim_s n_s \in \varprojlim_s \mathbb{Z}/N_s\mathbb{Z}$ then $g_{KK'} = g^0_{KK'}\mathrm{Fr}(t_{K'})^{-\bar{n}_{KK'}*}$, where $\mathrm{Fr}(t_{K'})^* = \{\mathrm{Fr}(t_{K'})_s\}_{s\geqslant 0}$ is the compatible system from Subsection 3.5.

Suppose L is a finite Galois extension of E in $E(p)$ containing K. Proceed similarly to obtain $L' \subset E(p)$ such that g induces an isomorphism of $\Gamma_L(p)$ and $\Gamma_{L'}(p)$, the corresponding compatible system $g_{LL'} = \{g_{LL's}\}_{s\geqslant 0}$ and the special admissible locally analytic system $g^0_{LL'} = \{g^0_{LL's}\}_{s\geqslant 0}$, where $g_{LL'} = g^0_{LL'}\mathrm{Fr}(t_{L'})^{-\bar{n}_{LL'}*}$, together with the corresponding $\eta_{LL'} \in \mathrm{Iso}^0(L, L')$ such that $g^0_{LL'\mathrm{an}} = \mathrm{d}(\eta_{LL'})\hat{\otimes}_{k_L} k_L(p)$. Here k_L is the residue field of L, $k_L \simeq \mathbb{F}_{p^{M_0}}$ and $\bar{n}_{LL'} \in \varprojlim \mathbb{Z}/p^{M_0 p^s}\mathbb{Z}$. Notice that all these maps depend on some choice of uniformising elements t_L and $t_{L'}$ in, respectively, L and L'.

The systems $g_{LL'}$ and $g_{KK'}$ are comparable because both come from the group isomorphisms $\Gamma_L(p) \longrightarrow \Gamma_{L'}(p)$ and $\Gamma_K(p) \longrightarrow \Gamma_{K'}(p)$ which are induced by g. If $I_{L/K}$ is the inertia subgroup of $\mathrm{Gal}(L/K)$ then there is a natural group embedding $I_{L/K} \subset \mathrm{Aut}^0(L) \subset \mathrm{Aut}^0(L_{\mathrm{ur}})$. Similarly, we have a group embedding for the inertia subgroup $I_{L'/K'}$ of $\mathrm{Gal}(L'/K')$ into $\mathrm{Aut}^0(L')$.

Let $\kappa : I_{L/K} \longrightarrow I_{L'/K'}$ be the group isomorphism induced by g. Then $\tau^* g_{LL's} = g_{LL's}\kappa(\tau)^*$, for any $\tau \in I_{L/K}$ and any $s \geqslant 0$. This implies that

$$\tau^* g_{LL'\mathrm{ur}} = g_{LL'\mathrm{ur}}\kappa(\tau)^*,$$

i.e. condition C from Subsection 3.7 holds in this case.

Let $\mu_{KK'} = \eta_{KK'}\mathrm{Fr}(t_{K'})^{-\bar{n}_{KK'}} \in \mathrm{Iso}(K, K')$ and $\mu_{LL'} = \eta_{LL'}\mathrm{Fr}(t_{K'})^{-\bar{n}_{LL'}} \in \mathrm{Iso}(L, L')$.

Proposition 6.1. *With the above notation:*
a) $\mu_{LL'}|_K = \mu_{KK'}$;
b) *for any* $\tau \in I_{L/K}$, $\tau\mu_{LL'} = \mu_{LL'}\kappa(\tau)$.

Proof. Let $\alpha = \mathrm{Fr}(t_{L'})^{\bar{n}_{LL'}}$. Consider K'_{ur} as a subfield in L'_{ur} and set $K''_{\mathrm{ur}} = \alpha(K'_{\mathrm{ur}}) \subset L'_{\mathrm{ur}}$. Then K''_{ur} is the maximal unramified p-extension of the complete discrete valuation field $K'' := \alpha(K') \subset E(p)$ in $E(p)$.

Let $\beta = \alpha|_{K'_{\mathrm{ur}}}$. Consider the following commutative diagram

$$\begin{array}{ccccc}
\bar{\mathcal{M}}_{L\mathrm{ur}} & \xrightarrow{g_{LL'\mathrm{ur}}} & \bar{\mathcal{M}}_{L'\mathrm{ur}} & \xrightarrow{\alpha^*_{L'L'\mathrm{ur}}} & \bar{\mathcal{M}}_{L'\mathrm{ur}} \\
\downarrow & & \downarrow & & \downarrow \\
\bar{\mathcal{M}}_{K\mathrm{ur}} & \xrightarrow{g_{KK'\mathrm{ur}}} & \bar{\mathcal{M}}_{K'\mathrm{ur}} & \xrightarrow{\beta^*_{K'K''\mathrm{ur}}} & \bar{\mathcal{M}}_{K''\mathrm{ur}}
\end{array}$$

where the vertical arrows come from natural embeddings of the corresponding Galois groups.

The systems $g^0_{LL'} = g_{LL'}\alpha^*_{L'L'}$ and $f_{KK''} := g_{KK'}\beta^*_{K'K''}$ are comparable, because they come from the compatible group isomorphisms $\Gamma_L(p) \longrightarrow \Gamma_{L'}(p)$ and $\Gamma_K(p) \xrightarrow{f} \Gamma_{K''}(p)$. In this situation, condition **C** is automatically satisfied and, by proposition 3.5, the admissibility of $g^0_{LL'}$ implies the admissibility of $f_{KK''}$. Because the group homomorphism f is compatible with ramification filtrations, we can apply the results of section 5 to deduce that $f_{KK''}$ is special admissible locally analytic and that there is an $\eta^1_{KK''} \in \mathrm{Iso}^0(K, K'')$ such that $f_{KK''\mathrm{an}} = \mathrm{d}(\eta^1_{KK''})\hat{\otimes}_k k(p)$ and $\eta_{LL'}|_K = \eta^1_{KK''}$.

Consider $\psi := \eta^{-1}_{KK'}\eta_{LL'}|_K \in \mathrm{Iso}^0(K', K'')$. Then

$$\begin{aligned}
\psi_{\mathrm{an}} &= \eta^{-1}_{KK'\mathrm{an}}\eta^1_{KK''\mathrm{an}} = (g^0_{KK'\mathrm{an}})^{-1}(g_{KK'}\beta^*_{K'K''})_{KK''\mathrm{an}} \\
&= \left(g^0_{KK'}{}^{-1} g_{KK'}\beta^*_{K'K''}\right)_{K'K''\mathrm{an}} = \left(\mathrm{Fr}(t_{K'})^{-\bar{n}_{KK'}}\beta\right)_{\mathrm{an}}.
\end{aligned}$$

Therefore by proposition 2.7,

$$\eta^{-1}_{KK'}\eta_{LL'}|_K = \mathrm{Fr}(t_{K'})^{-\bar{n}_{KK'}}\mathrm{Fr}(t_{L'})^{\bar{n}_{LL'}}|_K$$

or $\mu_{LL'}|_K = \mu_{KK'}$.

Part a) of our proposition is proved.

Consider the inertia subgroups $I_{L/K} \subset \mathrm{Gal}(L_{\mathrm{ur}}/K_{\mathrm{ur}})$, $I_{L'/K'} \subset \mathrm{Gal}(L'_{\mathrm{ur}}/K'_{\mathrm{ur}})$ and $I_{L'/K''} \subset \mathrm{Gal}(L'_{\mathrm{ur}}/K''_{\mathrm{ur}})$. As it was noticed earlier, the correspondence

$$\tau^* \mapsto \tau'^* = g^{-1}_{LL'\mathrm{ur}}\tau^* g_{LL'\mathrm{ur}}$$

induces a group isomorphism $\kappa : I_{L/K} \longrightarrow I_{L'/K'}$ such that $\kappa(\tau) = \tau'$.

We use the correspondence

$$\alpha^* : \tau' \mapsto \tau'' = \alpha^{-1}\tau'\alpha$$

to define the group isomorphism $\kappa_\alpha : I_{L'/K'} \longrightarrow I_{L'/K''}$ such that $\kappa_\alpha(\tau') = \tau''$. With this notation we have the following equality of compatible systems

$$\tau^*_{LL} g^0_{LL'} = g^0_{LL'}\tau''_{L'L'}{}^*,$$

where as earlier, $g^0_{LL'} = g_{LL'}\alpha^*_{L'L'}$.

Therefore, the equality $(\tau\eta_{LL'})_{\mathrm{an}} = (\tau^*_{LL}g^0_{LL'})_{\mathrm{an}} = (g^0_{LL'}\tau''^{\ *}_{L'L'})_{\mathrm{an}} = (\eta_{LL'}\tau'')_{\mathrm{an}}$ together with proposition 2.7 and the definition of τ'' imply that $\tau\eta_{LL'} = \eta_{LL'}\tau'' = \eta_{LL'}\alpha^{-1}\tau'\alpha$, i.e. $\tau\mu_{LL'} = \mu_{LL'}\tau'$.

The proposition is proved. □

Let $\mu := \varinjlim \mu_{KK'} : E(p) \longrightarrow E(p)$. Clearly, it is a continuous field isomorphism and $\mu(E) = E'$.

Proposition 6.2. $\mu^* = g$.

Proof. As earlier, let K and K' be Galois extensions of E and E', respectively, such that $g(\Gamma_K(p)) = \Gamma_{K'}(p)$.

By part b) of the above proposition 6.1, the correspondences $\mu^* : \tau \mapsto \mu^{-1}\tau\mu$ and $g : \tau \mapsto g(\tau)$ induce the same isomorphism of the inertia subgroups $I_K(p) \longrightarrow I_{K'}(p)$. Consider the induced isomorphism $I_K(p)^{\mathrm{ab}} \longrightarrow I_{K'}(p)^{\mathrm{ab}}$. With respect to the identifications of class field theory $I_K(p)^{\mathrm{ab}} = U_K$ and $I_{K'}(p)^{\mathrm{ab}} = U_{K'}$, where U_K and $U_{K'}$ are groups of principal units in K and K', respectively, this homomorphism is induced by the restriction of the field isomorphism $\mu_{KK'}$ on U_K. In addition, $\mu_{KK'}$ transforms the natural action of any $\tau \in \Gamma_E(p)$ on U_K into the natural action of $g(\tau) \in \Gamma_{E'}(p)$ on $U_{K'}$. Therefore, the two field automorphisms $\mu^{-1}\tau\mu|_{K'}$ and $g(\tau)|_{K'}$ of K' become equal after restricting on $U_{K'}$. This implies that they coincide on the whole field K', i.e. $\mu^{-1}\tau\mu \equiv g(\tau) \bmod \Gamma_{K'}(p)$, for any $\tau \in \Gamma_E(p)$. Because K is an arbitrary Galois extension of E in $E(p)$ this implies that $g = \mu^*$.

So, proposition 6.2 together with the characteristic p case of the Main Theorem are completely proved. □

7. Proof of the main theorem — the mixed characteristic case

In this section we assume that E is a field of characteristic 0. Clearly, this implies that the field E' is also of charactersitic 0.

7.1. Following the paper [10] introduce the categories Ψ, $\widetilde{\Psi}$ and the functor $\Phi : \Psi \longrightarrow \widetilde{\Psi}$.

The objects of Ψ are the field extensions L/K, where $[K : \mathbb{Q}_p] < \infty$, L is an infinite Galois extension of K in a fixed maximal p-extension $K(p)$ of K and $\Gamma_{L/K} = \mathrm{Gal}(L/K)$ is a p-adic Lie group. A morphism from L/K to an object L'/K' in Ψ is a continuous field embedding $f : L \longrightarrow L'$ such that $[L' : f(L)] < \infty$ and $f|_K$ is a field isomorphism of K and K'.

The objects of $\widetilde{\Psi}$ are couples $(\mathcal{K}, G)$ where $\mathcal{K}$ is a complete discrete valuation field of characteristic p with finite residue field and G is a closed subgroup of the group of all continuous automorphisms of $\mathcal{K}$. In addition, with respect to the induced topology G, is a compact finite dimensional

p-adic Lie group. A morphism from $(\mathcal{K}, G)$ to an object $(\mathcal{K}', G')$ in $\widetilde{\Psi}$ is a closed field embedding $f : \mathcal{K} \longrightarrow \mathcal{K}'$ such that $\mathcal{K}'$ is a finite separable extension of $f(\mathcal{K})$. In addition, $f(\mathcal{K})$ is G'-invariant and the corrspondence $\tau \mapsto \tau|_{f(\mathcal{K})}$ induces a group epimorphism from G' to G.

Let X be the Fontaine-Wintenberger field-of-norm functor, cf. [11]. Then the correspondence $L/K \mapsto (X(L), G_{L/K})$, where $G_{L/K} = \{X(\tau) \mid \tau \in \Gamma_{L/K}\}$, induces the functor $\Phi : \Psi \longrightarrow \widetilde{\Psi}$.

One of main results in [10] states that the functor Φ is fully faithful.

7.2. Let $\{E_\alpha/E, i_{\alpha\beta}\}_{\mathcal{I}}$ be an inductive system of objects in the category Ψ. From now on $\mathcal{I}$ is a set of indices α with a suitable partial ordering. The connecting morphisms $i_{\alpha\beta} \in \mathrm{Hom}_\Psi(E_\alpha, E_\beta)$ are the natural field embeddings defined for suitable couples $\alpha, \beta \in \mathcal{I}$. We can choose this inductive system to be large enough to satisfy the requirement $\varinjlim E_\alpha = E(p)$.

By applying the functor Φ, we obtain the inductive system $\{(\mathcal{E}_\alpha, G_\alpha), \tilde{i}_{\alpha\beta}\}_{\mathcal{I}}$ in the category $\widetilde{\Psi}$, where $(\mathcal{E}_\alpha, G_\alpha) = \Phi(E_\alpha/E)$ and $\tilde{\imath}_{\alpha\beta} = \Phi(i_{\alpha\beta})$, for all $\alpha \in \mathcal{I}$. Then $\varinjlim \mathcal{E}_\alpha = \mathcal{E}(p)$ is a maximal p-extension for each field $\mathcal{E}_\alpha$, $\alpha \in \mathcal{I}$.

Notice that the field embeddings $\tilde{\imath}_{\alpha\beta}$ induce group epimorphisms $\tilde{\jmath}_{\alpha\beta} : G_\beta \longrightarrow G_\alpha$ with corresponding projective system $\{G_\alpha, \tilde{\jmath}_{\alpha\beta}\}_{\mathcal{I}}$ such that $\varprojlim G_\alpha$ is identified via the functor X with $\Gamma_E(p)$. For any $\alpha \in \mathcal{I}$, we then have the identifications $\Gamma_{E_\alpha}(p) = \Gamma_{\mathcal{E}_\alpha}(p)$. These identifications are compatible with the ramification filtrations. This means that one can define the Herbrand function φ_α for the infinite extension E_α/E as the limit of Herbrand functions of all finite subextensions in E_α over E and

$$\Gamma_E(p)^{(v)} \cap \Gamma_{E_\alpha}(p) = \Gamma_{\mathcal{E}_\alpha}(p)^{(\varphi_\alpha(v))},$$

for all $v \geqslant 0$.

7.3. Consider the group isomorphism $g : \Gamma_E(p) \longrightarrow \Gamma_{E'}(p)$ from the statement of the Theorem. For $\alpha \in \mathcal{I}$, let $E'_\alpha \subset E'(p)$ be such that $g(\Gamma_{E_\alpha}(p)) = \Gamma_{E'_\alpha}(p)$. Then we have the corresponding injective system $\{E'_\alpha, i'_{\alpha\beta}\}_{\mathcal{I}}$ and $\varinjlim E'_\alpha = E'(p)$.

Clearly, for any $\alpha \in \mathcal{I}$,

- E'_α/E' is an object of Ψ;
- $\bar{g}_\alpha := g_\alpha \bmod \Gamma_{E_\alpha}(p) : \Gamma_{E_\alpha/E} \longrightarrow \Gamma_{E'_\alpha/E'}$ is a group isomorphism which is compatible with the ramification filtrations; in particular, this implies that the Herbrand functions for the infinite extensions E_α/E and E'_α/E' are equal;
- for any $v \geqslant 0$, $g_\alpha := g|_{\Gamma_{E_\alpha}(p)}$ induces a continuous group isomorphism of $\Gamma_E(p)^{(v)} \cap \Gamma_{E_\alpha}(p)$ and $\Gamma_{E'}(p)^{(v)} \cap \Gamma_{E'_\alpha}(p)$.

For $\alpha \in \mathcal{I}$, set $\Phi(E'_\alpha/E') = (\mathcal{E}'_\alpha, G'_\alpha)$ and $\Phi(i'_{\alpha\beta}) = \tilde{\imath}'_{\alpha\beta}$. Then we have an inductive system $\{(\mathcal{E}'_\alpha, G'_\alpha), \tilde{\imath}'_{\alpha\beta}\}_\mathcal{I}$ and $\varinjlim \mathcal{E}'_\alpha := \mathcal{E}'(p)$ is a maximal p-extension for each $\mathcal{E}'_\alpha$. As earlier, we obtain the projective system $\{G'_\alpha, \tilde{\jmath}'_{\alpha\beta}\}_\mathcal{I}$ and the field-of-norms functor allows us to identify the topological groups $\varprojlim G'_\alpha$ and $\Gamma_{E'}(p)$. Therefore, for any $\alpha \in \mathcal{I}$, we have an identification of the groups $\Gamma_{E'_\alpha}(p)$ and $\Gamma_{\mathcal{E}'_\alpha}(p)$.

This implies that for all $\alpha \in \mathcal{I}$, we have the following isomorphisms of topological groups:

- $\tilde{g}_\alpha := X(g_\alpha) : \Gamma_{\mathcal{E}_\alpha}(p) \longrightarrow \Gamma_{\mathcal{E}'_\alpha}(p)$ such that, for any rational number $v \geqslant 0$, $\tilde{g}_\alpha(\Gamma_{\mathcal{E}_\alpha}(p)^{(v)}) = \Gamma_{\mathcal{E}'_\alpha}(p)^{(v)}$;
- $X(\bar{g}_\alpha) : G_\alpha \longrightarrow G'_\alpha$ which maps the projective system $\{G_\alpha, \tilde{\jmath}_{\alpha\beta}\}_\mathcal{I}$ to the projective system $\{G'_\alpha, \tilde{\jmath}'_{\alpha\beta}\}_\mathcal{I}$.

7.4. By the characteristic p case of the Main Theorem for all $\alpha \in \mathcal{I}$, there are continuous field isomorphisms $\tilde{\mu}_\alpha : \mathcal{E}_\alpha \longrightarrow \mathcal{E}'_\alpha$ such that

- $\{\tilde{\mu}_\alpha\}_{\alpha\in\mathcal{I}}$ maps the inductive system $\{\mathcal{E}_\alpha, \tilde{\imath}_{\alpha\beta}\}_\mathcal{I}$ to the inductive system $\{\mathcal{E}'_\alpha, \tilde{\imath}'_{\alpha\beta}\}_\mathcal{I}$;
- $X(\bar{g}_\alpha)$ is induced by $\tilde{\mu}_\alpha$, i.e. if $\tau \in G_\alpha$ and $\tau' = X(\bar{g}_\alpha) \in G'_\alpha$ then $\tau\tilde{\mu}_\alpha = \tilde{\mu}_\alpha\tau'$.

Because Φ is a fully faithful functor, for all indices $\alpha \in \mathcal{I}$, there is a $\mu_\alpha \in \mathrm{Hom}_\Psi(E_\alpha/E, E'_\alpha/E')$ such that

- $\{\mu_\alpha\}_{\alpha\in\mathcal{I}}$ transforms the inductive system $\{E_\alpha/E, i_{\alpha\beta}\}_\mathcal{I}$ into the inductive system $\{E'_\alpha/E', i'_{\alpha\beta}\}_\mathcal{I}$;
- if $\tau \in \Gamma_{E_\alpha/E}$ and $\tau' = \bar{g}_\alpha(\tau) \in \Gamma_{E'_\alpha/E'}$ then $\tau\mu_\alpha = \mu_\alpha\tau'$.

Therefore, $\mu := \varinjlim \mu_\alpha$ is a continuous field isomorphism from $E(p)$ to $E'(p)$ such that $\tau\mu = \mu g(\tau)$, i.e. $g(\tau) = \mu^{-1}\tau\mu$, for $\tau \in \varprojlim \Gamma_{E_\alpha/E} = \Gamma_E(p)$ and $g(\tau) \in \varprojlim \Gamma_{E'_\alpha/E'} = \Gamma_{E'}(p)$.

The Main Theorem is completely proved.

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