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GROUPS OF AUTOMORPHISMS OF LOCAL FIELDS OF PERIOD p^M AND NILPOTENT CLASS $< p$

by Victor ABRASHKIN

ABSTRACT. — Suppose K is a finite field extension of $\mathbb{Q}_p$ containing a p^M-th primitive root of unity. For $1 \leqslant s < p$ denote by $K[s, M]$ the maximal p-extension of K with the Galois group of period p^M and nilpotent class s. We apply the nilpotent Artin–Schreier theory together with the theory of the field-of-norms functor to give an explicit description of the Galois groups of $K[s, M]/K$. As application we prove that the ramification subgroup of the absolute Galois group of K with the upper index v acts trivially on $K[s, M]$ iff $v > e_K(M + s/(p-1)) - (1 - \delta_{1s})/p$, where e_K is the ramification index of K and δ_{1s} is the Kronecker symbol.

RÉSUMÉ. — Soit K une extension finie de $\mathbb{Q}_p$ contenant une racine p^M-ième primitive de l'unité. Pour $1 \leqslant s < p$ on note $K[s, M]$ la p-extension maximale de K dont le groupe de Galois est de période p^M et de classe de nilpotence s. En utilisant la théorie d'Artin–Schreier nilpotente et la théorie du corps des normes on donne une description explicite du groupe de Galois de $K[s, M]/K$. Comme application de ce résultat on montre que le sous-groupe de ramification du groupe de Galois absolu de K de ramification supérieure v agit trivialement sur $K[s, M]$ si et seulement si $v > e_K(M + s/(p-1)) - (1 - \delta_{1s})/p$, où e_K est l'indice de ramification de K et δ_{1s} est le symbole de Kronecker.

Introduction

Everywhere in the paper $M \in \mathbb{N}$ is fixed and $p \neq 2$ is prime.

Let K be a complete discrete valuation field of characteristic 0 with finite residue field $k \simeq \mathbb{F}_{q_0}$, where $q_0 = p^{N_0}$, $N_0 \in \mathbb{N}$. Fix an algebraic closure $\bar{K}$ of K and denote by $K_{<p}(M)$ the maximal p-extension of K in $\bar{K}$ with the Galois group of nilpotent class $< p$ and exponent p^M. Then $\Gamma_{<p}(M) := \mathrm{Gal}(K_{<p}(M)/K) = \Gamma/\Gamma^{p^M} C_p(\Gamma)$, where $\Gamma = \mathrm{Gal}(\bar{K}/K)$ and $C_p(\Gamma)$ is the closure of the subgroup of commutators of order $\geqslant p$.

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Let $\{\Gamma^{(v)}\}_{v\geqslant 0}$ be the ramification filtration of Γ in upper numbering [14]. The importance of this additional structure on the Galois group Γ (which reflects arithmetic properties of K) can be illustrated by the local analogue of the Grothendieck Conjecture [5, 6, 13]: the knowledge of Γ together with the filtration $\{\Gamma^{(v)}\}_{v\geqslant 0}$ is sufficient to recover uniquely the isomorphic class of K in the category of complete discrete valuation fields.

Let $\{\Gamma_{<p}(M)^{(v)}\}_{v\geqslant 0}$ be the induced ramification filtration of $\Gamma_{<p}(M)$. Then the problem of arithmetical description of $\Gamma_{<p}(M)$ is the problem of explicit description of the filtration $\{\Gamma_{<p}(M)^{(v)}\}_{v\geqslant 0}$ in terms of generators of $\Gamma_{<p}(M)$.

An analogue of this problem was studied in [2, 3, 4] in the case of local fields $\mathcal{K}$ of characteristic p with residue field k. More precisely, let $\mathcal{G} = \mathrm{Gal}(\mathcal{K}_{sep}/\mathcal{K})$ and $\mathcal{G}_{<p}(M) = \mathcal{G}/\mathcal{G}^{p^M}C_p(\mathcal{G})$. In [2, 3] we developed a nilpotent version of the Artin–Schreier theory which allows us to construct identification of profinite groups $\mathcal{G}_{<p}(M) = G(\mathcal{L})$. Here $\mathcal{L}$ is a profinite Lie $\mathbb{Z}/p^M$-algebra of nilpotent class $< p$ and $G(\mathcal{L})$ is the pro-p-group, obtained from $\mathcal{L}$ by the Campbell–Hausdorff composition law, cf. Subsection 1.2 below for more details and [7, Subsection 1.1] for non-formal comments about nilpotent Artin–Schreier theory.

On the one hand, the above identification of $\mathcal{G}_{<p}(M)$ with $G(\mathcal{L})$ depends on a choice of uniformising element in $\mathcal{K}$ and, therefore, is not functorial (in particular, it can't be used directly to develop a nilpotent analog of classical local class field theory). On the other hand, the ramification subgroups $\mathcal{G}_{<p}(M)^{(v)}$ can be now described in terms of appropriate ideals $\mathcal{L}^{(v)}$ of the Lie algebra $\mathcal{L}$. The definition of these ideals essentially uses the extension of scalars $\mathcal{L}_k := \mathcal{L}\otimes W_M(k)$ of $\mathcal{L}$ (such operation does not exist in the category of p-groups) together with the appropriate explicit system of generators of $\mathcal{L}_k$, cf. Subsection 1.4. This justifies the advantage of the language of Lie algebras in the theory of p-extensions of local fields.

In this paper we apply the above characteristic p results to the study of similar properties in the mixed characteristic case, i.e. to the study of the group $\Gamma_{<p}(M)$ together with its ramification filtration. Our main tool is the Fontaine–Wintenberger theory of the field-of-norms functor [15]. Note also that we assume that K contains a primitive p^M-th root of unity and our methods generalize the approach from [1] where we considered the case $M = 1$. In some sense our theory can be treated as nilpotent version of Kummer's theory in the context of complete discrete valuation fields. As a result, we identify $\Gamma_{<p}(M)$ with the group $G(L)$, where L is a Lie $\mathbb{Z}/p^M$-algebra and for an appropriate ideal $\mathcal{J}$ of $\mathcal{L}$, we have the following exact

sequence of Lie algebras

$$0 \longrightarrow \mathcal{L}/\mathcal{J} \longrightarrow L \longrightarrow C_M \longrightarrow 0\,. \tag{0.1}$$

Here C_M is a cyclic group of order p^M with the trivial structure of Lie algebra over $\mathbb{Z}/p^M$.

As a first step in the study of L, we give an explicit description of the ideal $\mathcal{J}$. More generally, if $C_s(L)$ is the closure of the ideal of commutators of order $\geqslant s$ in L, then for $s \geqslant 2$, we have $C_s(L) \subset \mathcal{L}/\mathcal{J}$ and exact sequence (0.1) induces the exact sequences

$$0 \longrightarrow \mathcal{L}/\mathcal{L}(s) \longrightarrow L/C_s(L) \longrightarrow C_M \longrightarrow 0,$$

where all $\mathcal{L}(s)$ are ideals in $\mathcal{L}$. The main result of Section 3, Theorem 3.3, describes these ideals $\mathcal{L}(s)$ with $2 \leqslant s \leqslant p$ and gives in particular that $\mathcal{J} = \mathcal{L}(p)$.

Extension (0.1) splits in the category of $\mathbb{Z}/p^M$-modules and its structure can be given by explicit construction of a lift $\tau_{<p}$ of a generator of C_M to L and the appropriate differentiation $\mathrm{ad}\tau_{<p} \in \mathrm{End}(\mathcal{L}/\mathcal{J})$. The study of $\mathrm{ad}\tau_{<p}$ will be done in the next paper via methods used in the case $M = 1$ in [1].

In Section 4 we apply our approach to find for $1 \leqslant s < p$, the maximal upper ramification numbers $v(K[s,M]/K)$ of the maximal extensions $K[s,M]$ of K with Galois groups of period p^M and nilpotent class s. (The maximal upper ramification number for a finite extension K'/K in $\bar{K}$ is the maximal v_0 such that the ramification subgroups $\Gamma^{(v)}$ act trivially on K' if $v > v_0$.) This result can be stated in the following form, cf. Theorem 4.5 from Section 4:

If $[K:\mathbb{Q}_p] < \infty$ and $\zeta_M \in K$ then for $1 \leqslant s < p$,

$$v(K[s,M]/K) = e_K\left(M + \frac{s}{p-1}\right) - \frac{1-\delta_{s1}}{p}\,.$$

where e_K is the ramification index of $K/\mathbb{Q}_p$ and δ is the Kronecker symbol.

Remark. — The case $s = 1$ is very well-known and can be established without the assumption $\zeta_M \in K$. Is it possible to remove this restriction when $s > 1$?

Notation. — If $\mathfrak{M}$ is an R-module then its extension of scalars $\mathfrak{M} \otimes_R S$ will be very often denoted by $\mathfrak{M}_S$, cf. also another agreement in Subsection 1.1. Very often we drop off the indication to M from our notation and use just $K_{<p}, \Gamma_{<p}, \mathcal{G}_{<p}$ etc. instead of $K_{<p}(M), \Gamma_{<p}(M), \mathcal{G}_{<p}(M)$, etc.

1. Preliminaries

Let $\mathcal{K}$ be a complete discrete valuation field of characteristic p with residue field $k \simeq \mathbb{F}_{q_0}$, $q_0 = p^{N_0}$, and fixed uniformiser t_0. In other words, $\mathcal{K} = k((t_0))$.

As earlier, $\mathcal{G} = \mathrm{Gal}(\mathcal{K}_{sep}/\mathcal{K})$, $\mathcal{K}_{<p} = \mathcal{K}_{<p}(M)$ is the subfield of $\mathcal{K}_{sep}$ fixed by $\mathcal{G}^{p^M} C_p(\mathcal{G})$ and $\mathcal{G}_{<p} = \mathcal{G}_{<p}(M) = \mathrm{Gal}(\mathcal{K}_{<p}/\mathcal{K})$. The ramification filtration of $\mathcal{G}_{<p}$ was studied in details in [2, 3, 4]. We overview these results in the next subsections.

1.1. Compatible system of lifts modulo p^M

The uniformizer t_0 of $\mathcal{K}$ gives a p-basis for any separable extension $\mathcal{E}$ of $\mathcal{K}$, i.e. $\{1, t_0, \dots, t_0^{p-1}\}$ is a basis of the $\mathcal{E}^p$-module $\mathcal{E}$. We can use t_0 to construct a functorial on $\mathcal{E}$ (and on M) system of lifts $O(\mathcal{E})(= O_M(\mathcal{E}))$ of $\mathcal{E}$ modulo p^M. Recall that these lifts appear in the form $W_M(\sigma^{M-1}\mathcal{E})[t]$, where W_M is the functor of Witt vectors of length M, σ is the Frobenius morphism of taking p-th power and $t = (t_0, 0, \dots, 0) \in W_M(\mathcal{K})$.

Note that $t \in O(\mathcal{K}) \subset W_M(\mathcal{K})$, $t \bmod p = t_0$ and $\sigma t = t^p$. The lift $O(\mathcal{K})$ is naturally identified with the algebra of formal Laurent series $W_M(k)((t))$ in the variable t with coefficients in $W_M(k)$. A lift σ of the absolute Frobenius endomorphism of $\mathcal{K}$ to $O(\mathcal{K})$ is uniquely determined by the condition $\sigma t = t^p$. For a separable extension $\mathcal{E}$ of $\mathcal{K}$ we then have an extension of the Frobenius σ from $\mathcal{E}$ to $O(\mathcal{E})(= W_M(\sigma^{M-1}\mathcal{E})[t])$. As a result, we obtain a compatible system of lifts of the Frobenius endomorphism of $\mathcal{K}_{sep}$ to $O(\mathcal{K}_{sep}) = \varinjlim_{\mathcal{E}} O(\mathcal{E})$. For simplicity, we shall denote this lift also by σ. Note that σ is induced by the standard Frobenius endomorphism $W_M(\sigma)$ of $W_M(\mathcal{K}_{sep}) \supset O(\mathcal{K}_{sep})$.

Suppose $\eta_0 \in \mathrm{Aut}\,\mathcal{K}$ and let $W_M(\eta_0)$ be the induced automorphism of $W_M(\mathcal{K})$. If $W_M(\eta_0)(t) \in O(\mathcal{K})$ then $\eta := W_M(\eta_0)|_{O(\mathcal{K})}$ is a lift of η_0 to $O(\mathcal{K})$, i.e. $\eta \in \mathrm{Aut}\,O(\mathcal{K})$ and $\eta \bmod p = \eta_0$. With the above notation and assumption (in particular, $\eta(t) \in O(\mathcal{K})$) we have even more.

Proposition 1.1. — *Suppose $\mathcal{E}$ is separable over $\mathcal{K}$, $\eta_{\mathcal{E}0} \in \mathrm{Aut}\,\mathcal{E}$ and $\eta_{\mathcal{E}0}|_{\mathcal{K}} = \eta_0$. Then $\eta_{\mathcal{E}} := W_M(\eta_{\mathcal{E}0})|_{O(\mathcal{E})}$ is a lift of $\eta_{\mathcal{E}0}$ to $O(\mathcal{E})$ such that $\eta_{\mathcal{E}}|_{O(\mathcal{K})} = \eta$.*

Proof. — Indeed, using that $O(\mathcal{E}) = W_M(\sigma^{M-1}\mathcal{E})[t]$, we obtain

$$\eta_{\mathcal{E}}(W_M(\sigma^{M-1}\mathcal{E})) = W_M(\eta_{\mathcal{E}0})(W_M(\sigma^{M-1}\mathcal{E})) \subset W_M(\sigma^{M-1}\mathcal{E})) \subset O(\mathcal{E})\,,$$

and $\eta_{\mathcal{E}}(t) = W_M(\eta_{\mathcal{E}0})(t) = W_M(\eta_0)(t) \in O(\mathcal{K}) \subset O(\mathcal{E})$. So, $\eta_{\mathcal{E}}(O(\mathcal{E})) \subset O(\mathcal{E})$. Obviously, $\eta_{\mathcal{E}} \bmod p = \eta_{\mathcal{E}0}$. □

Remark. — The above lifts $\eta_{\mathcal{E}}$ commute with σ if and only if η commutes with σ, i.e. $\sigma(\eta(t)) = \eta(t^p)$. In particular, if $\eta(t) = t\alpha^{p^{M-1}}$ with $\alpha \in O(\mathcal{K})$ then $\sigma(\eta(t)) = t^p\alpha^{p^M} = \eta(t^p)$ (use that $\sigma(\alpha) \equiv \alpha^p \bmod pO(\mathcal{K})$).

A very special case of the above proposition appears as the following property:

> *If $\mathcal{E}/\mathcal{K}$ is Galois then the elements g of the group* $\mathrm{Gal}(\mathcal{E}/\mathcal{K})$ *can be naturally lifted to (commuting with σ) automorphisms of $O(\mathcal{E})$ via setting $g(t) = t$. Therefore, $O(\mathcal{K}_{sep})$ has a natural structure of a $\mathcal{G}$-module, the action of $\mathcal{G}$ commutes with σ, $O(\mathcal{K}_{sep})^{\mathcal{G}} = O(\mathcal{K})$ and $O(\mathcal{K}_{sep})|_{\sigma=\mathrm{id}} = W_M(\mathbb{F}_p)$.*

Everywhere below we shall use the following simplified notation.

Notation. — If $\mathfrak{M}$ is a $\mathbb{Z}/p^M$-module and $\mathcal{E}$ is a separable extension of $\mathcal{K}$ we set $\mathfrak{M}_{\mathcal{E}} := \mathfrak{M}_{O(\mathcal{E})} (= \mathfrak{M} \otimes_{\mathbb{Z}/p^M} O(\mathcal{E}))$. Similarly, we agree that $\mathfrak{M}_k := \mathfrak{M} \otimes_{\mathbb{Z}/p^M} W_M(k)$.

1.2. Categories of p-groups and Lie $\mathbb{Z}/p^M$-algebras, [11, 12]

If L is a Lie $\mathbb{Z}/p^M$-algebra of nilpotent class $< p$, denote by $G(L)$ the p-group obtained from L via the Campbell-Hausdorff composition law $\circ$ defined for $l_1, l_2 \in L$ via $\widetilde{\exp}(l_1 \circ l_2) = \widetilde{\exp} l_1 \cdot \widetilde{\exp} l_2$. Here

$$\widetilde{\exp}(x) = 1 + x + \cdots + x^{p-1}/(p-1)!$$

is the truncated exponential from L to the quotient of the enveloping algebra $\mathcal{A}$ of L modulo the p-th power of its augmentation ideal J. (This construction of the Campbell-Hausdorff operation was introduced in [2, Subsection 1.2].)

The correspondence $L \mapsto G(L)$ induces equivalence of the categories of finite Lie $\mathbb{Z}/p^M$-algebras and finite p-groups of exponent p^M of the same nilpotent class $1 \leqslant s_0 < p$. This equivalence can be extended to the similar categories of profinite Lie algebras and groups.

1.3. Witt pairing and Hilbert symbol, [8, 9]

Let

$$E(\alpha, X) = \exp\left(\alpha X + \frac{\sigma(\alpha)X^p}{p} + \cdots + \frac{\sigma^n(\alpha)X^{p^n}}{p^n} \ldots\right) \in W(k)[\![X]\!],$$

where $\alpha \in W(k)$, be the Shafarevich version of the Artin–Hasse exponential. Set $\mathbb{Z}^+(p) = \{a \in \mathbb{N} \mid \gcd(a,p) = 1\}$. Then any element $u \in \mathcal{K}^* \operatorname{mod} \mathcal{K}^{*p^M}$ can be uniquely written as

$$u = t_0^{a_0} \prod_{a \in \mathbb{Z}^+(p)} E(\alpha_a, t_0^a)^{1/a} \operatorname{mod} \mathcal{K}^{*p^M},$$

where $a_0 = a_0(u) \in \mathbb{Z} \operatorname{mod} p^M$ and all $\alpha_a = \alpha_a(u) \in W(k) \operatorname{mod} p^M$.

Let $\mathfrak{M}$ be a profinite free $W_M(k)$-module with the set of generators $\{D_0\} \cup \{D_{an} \mid a \in \mathbb{Z}^+(p), n \in \mathbb{Z}/N_0\}$. Use the correspondences

$$t_0 \mapsto D_0, \quad E(\alpha, t_0^a)^{1/a} \mapsto \sum_{n \operatorname{mod} N_0} \sigma^n(\alpha) D_{an}, \tag{1.1}$$

to identify $\mathcal{K}^*/\mathcal{K}^{*p^M}$ with a closed $\mathbb{Z}/p^M$-submodule in $\mathfrak{M}$. Under this identification we have $\mathcal{K}^*/\mathcal{K}^{*p^M} \otimes_{\mathbb{Z}/p^M} W_M(k) = \mathfrak{M}$.

Define the continuous action of the group $\langle \sigma \rangle = \operatorname{Gal}(k/\mathbb{F}_p)$ on $\mathfrak{M}$ as an extension of the natural action on $W_M(k)$ by setting $\sigma D_0 = D_0$ and $\sigma D_{an} = D_{a,n+1}$. Then $\mathcal{K}^*/\mathcal{K}^{*p^M} = \mathfrak{M}^{\operatorname{Gal}(k/\mathbb{F}_p)}$.

The Witt pairing

$$O(\mathcal{K})/(\sigma - \mathrm{id})O(\mathcal{K}) \times \mathcal{K}^*/\mathcal{K}^{*p^M} \longrightarrow \mathbb{Z}/p^M,$$

is given explicitly by the symbol $[f, g) = \operatorname{Tr}(\operatorname{Res}(f\, d_{\log} \operatorname{Col} g))$. Here $\operatorname{Tr} : W_M(k) \longrightarrow \mathbb{Z}/p^M$ is induced by the trace of the field extension $k/\mathbb{F}_p$, $f \in O(\mathcal{K})$ and $\operatorname{Col} g$ is the image of $g \in \mathcal{K}^*/\mathcal{K}^{*p^M}$ under the group homomorphism $\operatorname{Col} : \mathcal{K}^*/\mathcal{K}^{*p^M} \longrightarrow O_M^*(\mathcal{K})$ uniquely defined on the above free generators of $\mathcal{K}^*/\mathcal{K}^{*p^M}$ via the conditions $t_0 \mapsto t$ and $E(\alpha, t_0^a) \mapsto E(\alpha, t^a)$. The Witt pairing is non-degenerate and determines the identification

$$\mathcal{K}^*/\mathcal{K}^{*p^M} = \operatorname{Hom}_{\mathrm{cont}}(O(\mathcal{K})/(\sigma - \mathrm{id})O(\mathcal{K}), \mathbb{Z}/p^M).$$

It also coincides with the Hilbert symbol (in the case of local fields of characteristic p) and allows us to specify explicitly the reciprocity map $\kappa : \mathcal{K}^*/\mathcal{K}^{*p^M} \longrightarrow \mathcal{G}_{<p}^{ab}$ of class field theory. Namely, in the above notation we have $\kappa(g)f = f + [f, g)$.

1.4. Lie algebra $\mathcal{L}$ and identification η_M

Let $\widetilde{\mathcal{L}}$ be a free profinite Lie $\mathbb{Z}/p^M$-algebra with the module of (free) generators $\mathcal{K}^*/\mathcal{K}^{*p^M}$. Then the $W_M(k)$-module $\widetilde{\mathcal{L}}_k$ has the set of free generators

$$\{D_0\} \cup \{D_{an} \mid a \in \mathbb{Z}^+(p), n \in \mathbb{Z}/N_0\}. \tag{1.2}$$

If $C_p(\widetilde{\mathcal{L}})$ is the closure of the ideal of commutators of order $\geqslant p$, then $\mathcal{L} = \widetilde{\mathcal{L}}/C_p(\widetilde{\mathcal{L}})$ is the maximal quotient of $\widetilde{\mathcal{L}}$ of nilpotent class $< p$.

Remark. — $\mathcal{L}_k$ is a free object in the category of profinite Lie $W_M(k)$-algebras of nilpotent class $< p$ with the set of free generators (1.2).

We shall use the same notation D_0 and D_{an} for the images of the elements of (1.2) in $\mathcal{L}$. Choose $\alpha_0 \in W_M(k)$ such that $\operatorname{Tr}\alpha_0 = 1$.

Consider $e = \alpha_0 D_0 + \sum_{a\in\mathbb{Z}^+(p)} t^{-a}D_{a0} \in G(\mathcal{L}_{\mathcal{K}})$. If we set $D_{0n} := (\sigma^n\alpha_0)D_0$ then e can be written as $\sum_{a\in\mathbb{Z}^0(p)} t^{-a}D_{a0}$, where $\mathbb{Z}^0(p) = \mathbb{Z}^+(p)\cup\{0\}$.

Fix $f \in G(\mathcal{L}_{\mathcal{K}_{sep}})$ such that $\sigma f = e\circ f$. Then for $\tau\in\mathcal{G}$, the correspondence

$$\tau \mapsto (-f)\circ\tau f \in G(\mathcal{L}_{K_{sep}})|_{\sigma=\mathrm{id}} = G(\mathcal{L}),$$

induces the identification of profinite groups $\eta_M : \mathcal{G}_{<p} \simeq G(\mathcal{L})$.

Note that $f\in\mathcal{L}_{\mathcal{K}_{<p}}$ and $\mathcal{G}_{<p}$ strictly acts on the $\mathcal{G}$-orbit of f.

The above result is a covariant version of the nilpotent Artin–Schreier theory developed in [3], cf. also Subsection 1.1 in [7] for the relation between the covariant and contravariant versions of this theory and for appropriate non-formal comments.

We shall use below a fixed choice of f and use the notation for e and f without further references.

1.5. Relation to class field theory

The above identification η_M taken modulo $C_2(\mathcal{G}_{<p})$ gives an isomorphism of profinite p-groups

$$\eta_M^{ab} : \mathcal{G}_{<p}^{\mathrm{ab}} \longrightarrow \mathcal{L}^{ab} = \mathcal{L}/C_2(\mathcal{L}) = \mathfrak{M}^{\mathrm{Gal}(k/\mathbb{F}_p)} = \mathcal{K}^*/\mathcal{K}^{*p^M}.$$

Proposition 1.2. — *η_M^{ab} is induced by the inverse to the reciprocity map of local class field theory κ.*

Proof. — Indeed, let $\{\beta_i\}_{1\leqslant i\leqslant N_0}$ be a $\mathbb{Z}/p^M$-basis of $W_M(k)$ and let $\{\gamma_i\}_{1\leqslant i\leqslant N_0}$ be its dual basis with respect to the bilinear form induced by the trace of the field extension $W(k)[1/p]/\mathbb{Q}_p$.

If $a\in\mathbb{Z}^+(p)$ and $E(\beta_i, t_0^a)^{1/a} = D_{ia}$, then $D_{ia} = \sum_n \sigma^n(\beta_i)D_{an}$, and, therefore, $D_{a0} = \sum_i \gamma_i D_{ia}$. This implies that

$$e = \sum_{i,a} t^{-a}\gamma_i D_{ia} + \alpha_0 D_0 \bmod C_2(\mathcal{L}_{\mathcal{K}}),$$

$$f = \sum_{i,a} f_{ia}D_{ia} + f_0 D_0 \bmod C_2(\mathcal{L}_{\mathcal{K}_{sep}}),$$

where all $f_{ia}, f_0 \in O(\mathcal{K}_{<p})$, $\sigma f_{ia} - f_{ia} = \gamma_i t^{-a}$ and $\sigma f_0 - f_0 = \alpha_0$. From the definition of η_M it follows formally that for $\tau_{ia} = (\eta_M^{ab})^{-1} D_{ia}$ and $\tau_0 = (\eta_M^{ab})^{-1} D_0$, $\tau_{ia} f_{i_1 a_1} = f_{i_1 a_1} + \delta(ii_1)\delta(aa_1)$, $\tau_0 f_{i_1 a_1} = f_{i_1 a_1}$, $\tau_{ia} f_0 = f_0$ and $\tau_0 f_0 = f_0 + 1$. (Here δ is the Kronecker symbol.)

Now the explicit formula for the Hilbert symbol from Subsection 1.3 shows that $\kappa(E(\beta_i, t_0^a)^{1/a})$ and $\kappa(t_0)$ act by the same formulae as τ_{ia} and, resp., τ_0. □

1.6. Construction of lifts of analytic automorphisms

Let $\eta_0 \in \mathrm{Aut}\mathcal{K}$. Then there is a lift $\eta_{<p,0} \in \mathrm{Aut}\mathcal{K}_{<p}$ of η_0. (Use that the subgroup $\mathcal{G}^{p^M} C_p(\mathcal{G})$ of $\mathcal{G}$ is characteristic.) For any another such lift $\eta'_{<p,0}$, we have $\eta'_{<p,0}\eta^{-1}_{<p,0} \in \mathcal{G}_{<p}$.

The covariant version of the Witt–Artin–Schreier theory [3], Section 1 (cf. also [7, Subsection 1.1] and [1, Section 1]), gives explicit description of the automorphisms $\eta_{<p,0}$ in terms of the identification η_M. Consider a special case of this construction when η_0 admits a lift $\eta \in \mathrm{Aut}\, O(\mathcal{K})$ which commutes with σ, and therefore we have the appropriate lifts $\eta_{<p} \in \mathrm{Aut}\, O(\mathcal{K}_{<p})$, cf. Subsection 1.1. Then in terms of our fixed elements e and f, we have $\eta_{<p}(f) = c \circ (A \otimes \mathrm{id}_{O(\mathcal{K}_{<p})}) f$, where $c \in \mathcal{L}_{\mathcal{K}}$ and $A \in \mathrm{Aut}\mathcal{L}$ can be found from the relation

$$(\mathrm{id}_{\mathcal{L}} \otimes \eta)e = \sigma c \circ (A \otimes \mathrm{id}_{O(\mathcal{K})})e \circ (-c)\,,$$

cf. [3, Subsection 1.5], or [1, Proposition 1.1], and Subsection 3.2 below.

In other words, if $(A \otimes \mathrm{id}_{W_M(k)})(D_{a0}) = \widetilde{D}_{a0}$ then

$$\sum_{a\in\mathbb{Z}^0(p)} \eta(t)^{-a} D_{a0} = \sigma c \circ \left(\sum_{a\in\mathbb{Z}^0(p)} t^{-a}\widetilde{D}_{a0}\right) \circ (-c)\,.$$

Note that proceeding as in [3, Subsection 1.5.4], cf. also [1, Subsection 1.2], we can verify (this fact will be used systematically below) that with respect to the identification η_M, the automorphism A coincides with the conjugation $\mathrm{Ad}\,\eta_{<p} : \tau \mapsto \eta_{<p}^{-1}\,\tau\,\eta_{<p}$ (here $\tau \in \mathcal{G}_{<p}$).

1.7. Ramification filtration in $\mathcal{L}$

For $v \geqslant 0$, denote by $\mathcal{G}_{<p}^{(v)}$ the ramification subgroup of $\mathcal{G}_{<p}$ with the upper index v. Let $\mathcal{L}^{(v)}$ be the ideal of $\mathcal{L}$ such that $\eta_M(\mathcal{G}_{<p}^{(v)}) = G(\mathcal{L}^{(v)})$. The ideals $\mathcal{L}^{(v)}$ have the following explicit description.

First, for any $a \in \mathbb{Z}^0(p)$ and $n \in \mathbb{Z}$, set $D_{an} := D_{a,n \bmod N_0}$. In other words, we allow the second index in all D_{an} to take integral values and assume that $D_{an_1} = D_{an_2}$ iff $n_1 \equiv n_2 \bmod N_0$. For $s \geqslant 1$, agree to use the notation $(\bar{a}, \bar{n})_s$, where $\bar{a} = (a_1, \dots, a_s)$ has coordinates in $\mathbb{Z}^0(p)$ and $\bar{n} = (n_1, \dots, n_s) \in \mathbb{Z}^s$. Then we can attach to $(\bar{a}, \bar{n})_s$ the commutator $[\dots[D_{a_1 n_1}, D_{a_2 n_2}], \dots, D_{a_s n_s}]$ and set $\gamma(\bar{a}, \bar{n})_s = a_1 p^{n_1} + \dots + a_s p^{n_s}$. For any $\gamma \geqslant 0$, let $\mathcal{F}^0_{\gamma,-N}$ be the element from $\mathcal{L}_k$ given by

$$(1.3) \qquad \mathcal{F}^0_{\gamma,-N} = \sum_{\gamma(\bar{a},\bar{n})_s = \gamma} p^{n_1} a_1 \eta(\bar{n}) [\dots[D_{a_1 n_1}, D_{a_2 n_2}], \dots, D_{a_s n_s}]$$

where $\eta(\bar{n})$ equals $(s_1!(s_2 - s_1)! \dots (s - s_l)!)^{-1}$ if $0 \leqslant n_1 = \dots = n_{s_1} > n_{s_1+1} = \dots = n_{s_2} > \dots > n_{s_l} = \dots = n_s \geqslant -N$, and equals to zero otherwise. Then the main result of [4] (translated into the covariant setting, cf. [5, Subsections 1.1.2 and 1.2.4]) states that:

There is $\widetilde{N}(v) \in \mathbb{N}$ such that if we fix any $N \geqslant \widetilde{N}(v)$, then $\mathcal{L}^{(v)}$ is the minimal ideal of $\mathcal{L}$ such that for all $\gamma \geqslant v$, $\mathcal{F}^0_{\gamma,-N} \in \mathcal{L}^{(v)}_k$.

2. Filtration $\{\mathcal{L}(s)\}_{s \geqslant 1}$

In this section we define a decreasing central filtration $\{\mathcal{L}(s)\}_{s \geqslant 1}$ in the $\mathbb{Z}/p^M$-Lie algebra $\mathcal{L}$ from Subsection 1.4. Its definition depends on a choice of a special element $S \in \mathrm{m}(\mathcal{K}) := tW_M(k)[\![t]\!] \subset O(\mathcal{K})$. This element S (together with the appropriate elements S_0 and S' from its definition) will be specified in Section 4, where we apply our results to the mixed characteristic case.

2.1. Elements $S_0, S', S \in \mathrm{m}(\mathcal{K})$

Let $[p]$ be the isogeny of multiplication by p in the formal group $\mathrm{Spf}\, \mathbb{Z}_p[\![X]\!]$ over $\mathbb{Z}_p$ with the logarithm $X + X^p/p + \dots + X^{p^n}/p^n + \dots$.

Choose $S_0 \in \mathrm{m}(\mathcal{K})$ and set $S' = [p]^{M-1}(S_0)$ and $S = [p]^M(S_0)$. Then $S, S' \in \mathrm{m}(\mathcal{K})$, they both depend only on the residue $S_0 \bmod p$ and $S = \sigma S'$. In particular, if $e^* \in \mathbb{N}$ is such that $S \bmod p$ generates the ideal $(t_0^{e^*})$ in $k[\![t_0]\!]$ then $e^* \equiv 0 \bmod p^M$.

Proposition 2.1.

(a) $dS=0$ *in* $\Omega^1_{O(\mathcal{K})}$;

(b) *there is* $S''\in \mathrm{m}(\mathcal{K})$, *such that* $S=S'(p+S'')$;

(c) *there are* $\eta_0,\eta_1\in W_M(k)[\![t]\!]^\times$ *and* $\eta_2\in W_M(k)[\![t]\!]$ *such that*

$$S=t^{e^*}\eta_0+pt^{e^*/p}\eta_1+p^2\eta_2.$$

Proof.

(a) The congruence $[p]X\equiv X^p \bmod p\mathbb{Z}_p[\![X]\!]$ implies that $d([p]X)\in p\mathbb{Z}_p[\![X]\!]$. Therefore, $dS=0$ in $\Omega^1_{O(\mathcal{K})}$.

(b) Note that $[p](X)\equiv pX \bmod X^2$. Therefore, there are $w_i\in\mathbb{Z}_p$ such that $S=[p]S'=pS'+\sum_{i\geqslant 2}w_iS'^i$ and we can take $S''=\sum_{i\geqslant 1}w_{i+1}S'^i$.

(c) The t_0-adic valuation of $S' \bmod p$ equals e^*/p. Then our property is implied by the following equivalence in $\mathbb{Z}_p[\![X]\!]$

$$[p](X)\equiv pX+X^p \bmod (pX^{p^2-p+1},p^2X).$$ □

Remark. — We shall use below property (a) in the following form:

If $s\in\mathbb{N}$ *and* $S^s=\sum_{l\geqslant 1}\gamma_{ls}t^l$, *where all* $\gamma_{ls}\in W_M(k)$, *then* $l\gamma_{ls}=0$.

2.2. Morphism ι

Let $\mathcal{U}=(1+t_0k[\![t_0]\!])^\times$ be the $\mathbb{Z}_p$-module of principal units in $\mathcal{K}$. Then $\mathcal{U}/\mathcal{U}^{p^M}$ is a closed $\mathbb{Z}/p^M$-submodule in $\mathcal{K}^*/\mathcal{K}^{*p^M}$. Note that $\mathrm{m}(\mathcal{K})=W_M(\mathrm{m}_{\mathcal{K}})\cap O(\mathcal{K})$, where $\mathrm{m}_{\mathcal{K}}$ is the maximal ideal in the valuation ring of $\mathcal{K}$. Consider a (unique) continuous homomorphism

$$\iota:\mathcal{U}\longrightarrow \mathrm{m}(\mathcal{K})$$

such that for any $\alpha\in W_M(k)$ and $a\in\mathbb{Z}^+(p)$, $\iota: E(\alpha,t_0^a)\mapsto \alpha t^a$ (here E is the Shafarevich function, cf. Subsection 1.3).

Then ι induces an identification of $\mathcal{U}/\mathcal{U}^{p^M}$ with the closed $W_M(k)$-submodule

$$\mathrm{Im}\,\iota=\left\{\sum_{a\in\mathbb{Z}^+(p)}\alpha_at^a \,\middle|\, \alpha_a\in W_M(k)\right\}$$

in $O(\mathcal{K})$. This submodule is topologically generated over $W_M(k)$ by all t^a with $a\in\mathbb{Z}^+(p)$.

2.3. Definition of $\{\mathcal{L}(s)\}_{s\geqslant 1}$

Set $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(1)} = \mathcal{K}^*/\mathcal{K}^{*p^M}$. For $s\geqslant 1$, let $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)} = (\operatorname{Im}\iota)S^s$ with respect to the identification $\mathcal{U}/\mathcal{U}^{p^M} = \operatorname{Im}\iota$ from Subsection 2.2. Note, that $S=\sigma S'$ implies that for any $s\in\mathbb{N}$, $(\operatorname{Im}\iota)S^s\subset\operatorname{Im}\iota$.

Definition. — *$\{\mathcal{L}(s)\}_{s\geqslant 1}$ is the minimal central filtration of ideals of the Lie algebra $\mathcal{L}$ such that for all $s\geqslant 1$, $\mathcal{L}(s)\supset(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}$.*

The ideals $\mathcal{L}(s)$ can be defined by induction on s as follows. Let $\mathcal{L}(1)=\mathcal{L}$; then for $s\geqslant 1$, the ideal $\mathcal{L}(s+1)$ is generated by the elements of $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}$ and $[\mathcal{L}(s),\mathcal{L}]$. Note also that for any s, $(\mathcal{K}^*/\mathcal{K}^{*p^M})\cap\mathcal{L}(s) = (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}$. (Use that $\mathbb{Z}/p^M$-module $\mathcal{L}(s)$ is isomorphic to $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}\oplus(\mathcal{L}(s)\cap C_2(\mathcal{L}))$.

In addition, for any $s\geqslant 1$, the quotients $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}/(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}$ are free $\mathbb{Z}/p^M$-modules. This easily implies that all $\mathcal{L}(s)/\mathcal{L}(s+1)$ are also free $\mathbb{Z}/p^M$-modules.

2.4. Characterization of $\{\mathcal{L}(s)\}_{s\geqslant 1}$ in terms of $e\in\mathcal{L}_{\mathcal{K}}$

Recall that $e=\sum_{a\in\mathbb{Z}^0(p)} t^{-a}D_{a0}$, cf. Subsection 1.4.

Proposition 2.2. — *The filtration $\{\mathcal{L}(s)\}_{s\geqslant 1}$ is the minimal central filtration in $\mathcal{L}$ such that $\mathcal{L}(1)=\mathcal{L}$ and for all $s\geqslant 1$,*

$$S^s e\in\mathcal{L}_{\mathrm{m}(\mathcal{K})}+\mathcal{L}(s+1)_{\mathcal{K}}.$$

Proof. — We need the following two lemmas.

Lemma 2.3. — *For all $s\geqslant 1$ and $\alpha_a\in W_M(k)$ where $a\in\mathbb{Z}^+(p)$, we have*

$$\prod_{a\in\mathbb{Z}^+(p)} E(\alpha_a,t_0^a)\in(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}$$
$$\Leftrightarrow \prod_{a\in\mathbb{Z}^+(p)} E(\alpha_a,t_0^a)^{1/a}\in(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}.$$

Proof of Lemma 2.3. — We must prove that

$$\sum_{a\in\mathbb{Z}^+(p)}\alpha_a t^a\in S^s\mathrm{m}(\mathcal{K}) \quad\Leftrightarrow\quad \sum_{a\in\mathbb{Z}^+(p)}\frac{1}{a}\alpha_a t^a\in S^s\mathrm{m}(\mathcal{K}).$$

Let $S^s=\sum_{l\geqslant 1}\gamma_{ls}t^l$ with $\gamma_{ls}\in W_M(k)$, then $l\gamma_{ls}=0$, cf. Remark in Subsection 2.1.

Suppose

$$\sum_{a\in\mathbb{Z}^+(p)} \alpha_a t^a \in S^s\mathrm{m}(\mathcal{K}).$$

Then $\sum_a \alpha_a t^a = (\sum_b \beta_b t^b)(\sum_l \gamma_{ls} t^l)$, where $\sum_b \beta_b t^b \in \mathrm{m}(\mathcal{K})$ and $\alpha_a = \sum_{a=b+l} \beta_b\gamma_{ls}$. This implies

$$\frac{1}{a}\alpha_a = \sum_{a=b+l} \frac{1}{a}\beta_b\gamma_{ls} = \sum_{a=b+l} \frac{1}{b}\beta_b\gamma_{ls},$$

because if $a = b + l$ and $a \in \mathbb{Z}^+(p)$ then $b \in \mathbb{Z}^+(p)$ and

$$\frac{1}{a}\gamma_{ls} - \frac{1}{b}\gamma_{ls} = \frac{-l\gamma_{ls}}{ab} = 0.$$

So,

$$\sum_{a\in\mathbb{Z}^+(p)} \frac{1}{a}\alpha_a t^a = \left(\sum_{b\in\mathbb{Z}^+(p)} \frac{1}{b}\beta_b t^b\right)\left(\sum_l \gamma_{ls} t^l\right)$$

and

$$\sum_a \frac{1}{a}\alpha_a t^a \in S^s\mathrm{m}(\mathcal{K}).$$

Proceeding in the opposite direction we obtain the inverse statement. The lemma is proved. □

Lemma 2.4. — *If $s \geqslant 1$ and all $\alpha_a \in W_M(k)$ then*

$$\prod_{a\in\mathbb{Z}^+(p)} E(\alpha_a, t_0^a)^{1/a} \in (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)} \Leftrightarrow \sum_{a\in\mathbb{Z}^+(p)} \alpha_a D_{a0} \in (\mathcal{K}^*/\mathcal{K}^{*p^M})_k^{(s)}$$

Proof of Lemma 2.4. — Suppose

$$\prod_{a\in\mathbb{Z}^+(p)} E(\alpha_a, t_0^a)^{1/a} \in (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}.$$

Choose a $W_M(\mathbb{F}_p)$-basis $\{\beta_i\}$ of $W_M(k)$, and let $\{\gamma_i\}$ be its dual with respect to the trace form. Then for any i,

$$\prod_{a\in\mathbb{Z}^+(p)} E(\beta_i\alpha_a, t_0^a)^{1/a} \in (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}.$$

In other words (use (1.1) from Subsection 1.3),

$$c_i = \sum_{\substack{a\in\mathbb{Z}^+(p)\\ n\in\mathbb{Z}/N_0\mathbb{Z}}} \sigma^n(\beta_i)\sigma^n(\alpha_a)D_{an} \in \left(\mathcal{K}^*/\mathcal{K}^{*p^M}\right)^{(s)} \subset \mathcal{L}(s),$$

and

$$\sum_i \gamma_i c_i = \sum_{a\in\mathbb{Z}^+(p)} \alpha_a D_{a0} \in \mathcal{L}(s)_k.$$

Suppose now that $\sum_{a\in\mathbb{Z}^+(p)}\alpha_a D_{a0}\in\mathcal{L}(s)_k$. Then

$$\sum_{a\in\mathbb{Z}^+(p)}\alpha_a D_{a0}\in(\mathcal{K}^*/\mathcal{K}^{*p^M})_k^{(s)},$$

and, therefore,

$$\sum_{\substack{a\in\mathbb{Z}^+(p)\\ n\in\mathbb{Z}/N_0\mathbb{Z}}}\sigma^n(\alpha_a)D_{an}\in(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}.$$

This means, that

$$\prod_{a\in\mathbb{Z}^+(p)}E(\alpha_a,t_0^a)^{1/a}\in(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}.$$

The lemma is proved. □

Now we can finish the proof of our proposition. If, as earlier, $S^s=\sum_{l\geqslant 1}\gamma_{ls}t^l$ with $\gamma_{ls}\in W_M(k)$, then $(\operatorname{Im}\iota)S^s$ is the $W_M(k)$-submodule in $\mathrm{m}(\mathcal{K})$ generated by the elements $t^{a_1}S^s=\sum_{l\geqslant 1}\gamma_{ls}t^{l+a_1}$, $a_1\in\mathbb{Z}^+(p)$. The above lemmas imply then that $\{\mathcal{L}(s)\}_{s\geqslant 1}$ is the minimal central filtration in $\mathcal{L}$ such that $\mathcal{L}(1)=\mathcal{L}$ and for all $a_1\in\mathbb{Z}^+(p), s\geqslant 1$,

$$\sum_{l\geqslant 1}\gamma_{ls}D_{a_1+l,0}\in\mathcal{L}(s+1)_k\,.$$

On the other hand,

$$S^se=\sum_{\substack{a\in\mathbb{Z}^0(p)\\ l\geqslant 1}}\gamma_{ls}t^{-(a-l)}D_{a0}\equiv\sum_{a_1\in\mathbb{Z}^+(p)}\left(\sum_{l\geqslant 1}\gamma_{ls}D_{a_1+l,0}\right)t^{-a_1}$$

modulo $\mathcal{L}_{\mathrm{m}(\mathcal{K})}$. Therefore,

$$S^se\in\mathcal{L}_{\mathrm{m}(\mathcal{K})}+\mathcal{L}(s+1)_{\mathcal{K}}$$
$$\Leftrightarrow\sum_l\gamma_{ls}D_{a_1+l,0}\in\mathcal{L}(s+1)_k\quad\text{for all } a_1\in\mathbb{Z}^+(p).$$

The proposition is proved. □

Definition. — $\mathcal{N}=\sum_{s\geqslant 1}S^{-s}\mathcal{L}(s)_{\mathrm{m}(\mathcal{K})}$.

Note that $\mathcal{N}$ is a Lie $W_M(\mathbb{F}_p)$-subalgebra in $\mathcal{L}_{\mathcal{K}}$. With this notation Proposition 2.2 implies the following characterization of the filtration $\{\mathcal{L}(s)\}_{s\geqslant 1}$.

Corollary 2.5. — $\{\mathcal{L}(s)\}_{s\geqslant 1}$ *is the minimal central filtration in* $\mathcal{L}$ *such that* $\mathcal{L}(1)=\mathcal{L}$ *and* $e\in\mathcal{N}$.

Proof. — It will be sufficient to verify that

$$e \in \mathcal{N} \Leftrightarrow \forall s \geqslant 1,\ S^s e \in \mathcal{L}_{\mathrm{m}(\mathcal{K})} + \mathcal{L}(s+1)_{\mathcal{K}}\,.$$

The “if” part is obvious. The “only if” part can be proved by induction on s via the following property:

If $l'(s) \in \mathcal{L}(s)_{\mathcal{K}}$ and $Sl'(s) \in \mathcal{L}_{\mathrm{m}(\mathcal{K})} + \mathcal{L}(s+1)_{\mathcal{K}}$ then $l'(s) \in S^{-1}\mathcal{L}(s)_{\mathrm{m}(\mathcal{K})} + \mathcal{L}(s+1)_{\mathcal{K}}$ (use that $\mathcal{L}(s)/\mathcal{L}(s+1)$ is free $\mathbb{Z}/p^M$-module). □

2.5. Element $e^{\dagger} \in G(\mathcal{L}_{\mathcal{K}})$

Recall that $S \bmod p$ generates the ideal $(t_0^{e^*})$ in $k[\![t_0]\!]$. Therefore, the projections of the elements of the set

$$\left\{S^{-m}t^b \mid 1 \leqslant b < e^*, \gcd(b,p) = 1, m \in \mathbb{N}\right\} \cup \{\alpha_0\}$$

form a basis of $O(\mathcal{K})/(\sigma - \mathrm{id})O(\mathcal{K})$ over $W_M(k)$.

Proposition 2.6. — *There are $V_{(0)} \in \mathcal{L}$, $x \in S\mathcal{N}$ and $V_{(b,m)} \in \mathcal{L}_k$, where $m \geqslant 1$, $1 \leqslant b < e^*$, $\gcd(b,p) = 1$, such that*

(a) $e^{\dagger} := \sum_{m,b} S^{-m}t^b V_{(b,m)} + \alpha_0 V_{(0)} \in \mathcal{N}$;

(b) $e^{\dagger} = (-\sigma x) \circ e \circ x$.

Proof. — Note that $S \in \sigma\mathrm{m}(\mathcal{K})$ implies that the sets $\{t^{-a} \mid a \in \mathbb{Z}^+(p)\}$ and $\{S^{-m}t^b \mid m \in \mathbb{N}, \gcd(b,p) = 1, 1 \leqslant b < e^*\}$ generate the same $W_M(k)$-submodules in $O(\mathcal{K})/\mathrm{m}(\mathcal{K})$. This implies the existence of $V_{(0)}^{(0)} \in \mathcal{L}$ and $V_{(b,m)}^{(0)} \in \mathcal{L}_k$ such that

$$e \equiv e_0^{\dagger} \bmod \mathcal{L}_{\mathrm{m}(\mathcal{K})} \tag{2.1}$$

where $e_0^{\dagger} := \sum_{(b,m)} S^{-m}t^b V_{(b,m)}^{(0)} + \alpha_0 V_{(0)}^{(0)}$.

For $i \geqslant 1$, let $\mathcal{N}^{(i)} = \sum_{s \geqslant i} S^{-s}\mathcal{L}(s)_{\mathrm{m}(\mathcal{K})}$. Then

- $\mathcal{N}^{(i)} = S^{-i}\mathcal{L}(i)_{\mathrm{m}(\mathcal{K})} + \mathcal{N}^{(i+1)}$;
- $\left[\mathcal{N}^{(i)}, \mathcal{N}\right] \subset \mathcal{N}^{(i+1)}$.

In particular, relation (2.1) implies that $e = e_0^{\dagger} + \sigma x_0 - x_0$, where $x_0 \in \mathcal{L}_{\mathrm{m}(\mathcal{K})}$, and we obtain

$$(-\sigma x_0) \circ e \circ x_0 \equiv e_0^{\dagger} \bmod S\mathcal{N}^{(2)} \tag{2.2}$$

(use that $x_0, \sigma x_0 \in \mathcal{L}_{\mathrm{m}(\mathcal{K})} \subset S\mathcal{N}^{(1)}$). Now we need the following lemma.

LEMMA 2.7. — *Suppose* $\mathfrak{M}$ *is a* $\mathbb{Z}_p$*-module and* $i_0 \in \mathbb{N}$*. Then for any* $l \in S^{-i_0}\mathfrak{M}_{\mathrm{m}(\mathcal{K})}$*, there are* $l_{(0)} \in \mathfrak{M}$*,* $\tilde{l} \in S^{-i_0}\mathfrak{M}_{\mathrm{m}(\mathcal{K})}$ *and* $l_{(b,m)} \in \mathfrak{M}_k$*, where* $1 \leqslant m \leqslant i_0$*,* $\gcd(p,b) = 1$ *and* $1 \leqslant b < e^*$*, such that*

$$l = \sum_{b,m} S^{-m} t^b l_{(b,m)} + \alpha_0 l_{(0)} + \sigma\tilde{l} - \tilde{l}.$$

Proof of Lemma 2.7. — It will be sufficient to consider the case $\mathfrak{M} = \mathbb{Z}_p$. In other words, we must prove the following statement:

For any $s \in S^{-i_0}\mathrm{m}(\mathcal{K})$*, there are* $\beta_{(0)} \in W_M(\mathbb{F}_p)$*,* $\tilde{s} \in S^{-i_0}\mathrm{m}(\mathcal{K})$ *and* $\beta_{(b,m)} \in W_M(k)$*, where* $1 \leqslant m \leqslant i_0$*,* $\gcd(b,p) = 1$ *and* $1 \leqslant b < e^*$*, such that*

$$s = \sum_{b,m} \beta_{(b,m)} S^{-m} t^b + \alpha_0\beta_{(0)} + \sigma\tilde{s} - \tilde{s}.$$

We can assume that $s = t^{a_0}/S^{i_0}$, where $1 \leqslant a_0 < e^*$, $i_0 \in \mathbb{N}$ and our lemma is proved for all elements s from $pS^{-i_0}\mathrm{m}(\mathcal{K}) + t^{a_0}S^{-i_0}\mathrm{m}(\mathcal{K})$.

If $\gcd(a_0, p) = 1$ there is nothing to prove. Otherwise, $a_0 = pa_1$ and $s = s' + \sigma(s') - s'$ with $s' = t^{a_1}/S'^{i_0} = t^{a_1}(p + S'')/S^{i_0}$. It remains to note that $s' \in pS^{-i_0}\mathrm{m}(\mathcal{K}) + t^{a_0}S^{-i_0}\mathrm{m}(\mathcal{K})$, because $S'' \bmod p \in (t_0^{e^0})$, where $e^0 := e^*(1-1/p)$, and $a_1 + e^0 = a_0/p + e^0 > a_0$ (use that $a_0 < e^*$). ☐

Continue the proof of Proposition 2.6. Clearly, it is implied by the following lemma.

LEMMA 2.8. — *For all* $i \geqslant 0$*, there are* $x_i \in S\mathcal{N}$*,* $V_{(b,m)}^{(i)} \in \mathcal{L}_k$ *and* $V_{(0)}^{(i)} \in \mathcal{L}$ *such that:*

(a_1) $x_{i+1} \equiv x_i \bmod S\mathcal{N}^{(i+1)}$;

(a_2) $V_{(b,m)}^{(i+1)} \equiv V_{(b,m)}^{(i)} \bmod \mathcal{L}(i+2)_k$;

(a_3) $V_{(0)}^{(i+1)} \equiv V_{(0)}^{(i)} \bmod \mathcal{L}(i+2)$

(b) *if* $e_i^\dagger = \sum_{b,m} S^{-m}t^b V_{(b,m)}^{(i)} + \alpha_0 V_0^{(i)}$ *then*

$$(-\sigma x_i) \circ e \circ x_i \equiv e_i^\dagger \bmod S\mathcal{N}^{(i+2)}.$$

Proof of Lemma 2.8. — Use the elements $V_{(b,m)}^{(0)}, V_{(0)}^{(0)}, e_0^\dagger$ and x_0 from the beginning of the proof of Proposition 2.6. Then part (b) holds for $i = 0$ by (2.2).

Let $i_0 \geqslant 1$ and assume that our Lemma is proved for all $i < i_0$. Let $l \in S^{-i_0}\mathcal{L}(i_0+1)_{\mathrm{m}(\mathcal{K})}$ be such that

$$e_{i_0-1}^\dagger - (-\sigma x_{i_0-1}) \circ e \circ x_{i_0-1} \equiv l \bmod S\mathcal{N}^{(i_0+2)}.$$

Apply Lemma 2.7 to $\mathfrak{M} = \mathcal{L}(i_0+1)$ and $l \in S^{-i_0}\mathcal{L}(i_0+1)_{\mathrm{m}(\mathcal{K})}$. This gives us the appropriate elements $l_{(b,m)} \in \mathcal{L}(i_0+1)_k$, $l_{(0)} \in \mathcal{L}(i_0+1)$

and $\tilde{l} \in S^{-i_0}\mathcal{L}(i_0+1)_{\mathrm{m}(\mathcal{K})}$. Note that the elements $l_{(b,m)}$ are defined only for $1 \leqslant m \leqslant i_0$. Extend their definition by setting $l_{(b,m)} = 0$ if $m > i_0$. Then the case $i = i_0$ of Lemma 2.8 holds with $V^{(i_0)}_{(b,m)} = V^{(i_0-1)}_{(b,m)} + l_{(b,m)}$, $V^{(i_0)}_{(0)} = V^{(i_0-1)}_{(0)} + l_{(0)}$ and $x_{i_0} = x_{i_0-1} + \tilde{l}$. (We use here that $S\mathcal{N}^{(i_0+1)} = S^{-i_0}\mathcal{L}(i_0+1)_{\mathrm{m}(\mathcal{K})} + S\mathcal{N}^{(i_0+2)}$.)

Lemma 2.8 and Proposition 2.6 are completely proved. □

Proposition 2.6(b) implies that the elements $\sigma^n V_{(b,m)}$, $n \in \mathbb{Z}/N_0$, together with $V_{(0)}$ form a system of free topological generators of $\mathcal{L}_k$. Suppose $\{\beta_i\}_{1\leqslant i\leqslant N_0}$ and $\{\gamma_i\}_{1\leqslant i\leqslant N_0}$ are the $\mathbb{Z}/p^M$-bases of $W_M(k)$ from the proof of Proposition 1.2. Proceeding similarly to that proof introduce the elements

$$V_{(b,m),i} := \sum_{n\in\mathbb{Z}/N_0} \sigma^n(\beta_i)\sigma^n(V_{(b,m)})\,.$$

Then all $V_{(b,m)}$ can be recovered via the relation $V_{(b,m)} = \sum_i \gamma_i V_{(b,m),i}$. This implies that the elements $V_{(b,m),i}$ together with $V_{(0)}$ form a system of free topological generators of $\mathcal{L}$. (Recall that $\mathcal{L}$ is a free object in the category of Lie $\mathbb{Z}/p^M$-algebras of nilpotent class $< p$.) Therefore, we can introduce the weight function wt on $\mathcal{L}$ by setting for all b, m, i, $\mathrm{wt}(V_{(b,m),i}) = m$ and $\mathrm{wt}(V_{(0)}) = 1$. Note that by Proposition 2.6(b) we have that $e^\dagger \in \mathcal{N}$ if and only if $e \in \mathcal{N}$. Now Proposition 2.2 implies the following corollary.

Corollary 2.9. — *For any $s \geqslant 1$, $\mathcal{L}(s) = \{l \in \mathcal{L} \mid \mathrm{wt}(l) \geqslant s\}$.*

3. The groups $\widetilde{\mathcal{G}}_h$ and $\mathcal{G}_h$

3.1. Automorphism h

Let $S \in O(\mathcal{K})$ be the element introduced in Subsection 2.1. Let $h_0 \in \mathrm{Aut}(\mathcal{K})$ be such that $h_0|_k = \mathrm{id}$ and $h_0(t_0) = t_0E(1, S \bmod p)$. Then h_0 admits a lift to $h \in \mathrm{Aut}\, O(\mathcal{K})$ such that $h|_{W_M(k)} = \mathrm{id}$ and $h(t) = tE(1, S)$. Recall that $O(\mathcal{K}) = W_M(k)((t))$. If $n \in \mathbb{N}$ then denote by $h^n(t)$ the n-th superposition of the formal power series $h(t)$.

Proposition 3.1. — *For any $n \in \mathbb{N}$, $h^n(t) \equiv tE(n, S) \bmod S^p\mathrm{m}(\mathcal{K})$*

Proof. — If $n = 1$ there is nothing to prove. Suppose proposition is proved for some $n \in \mathbb{N}$. Then

$$h^{n+1}(t) = h^n(h(t)) \equiv tE(1, S)E(n, S(h(t))) \bmod \mathrm{m}(\mathcal{K})S(h(t))^p.$$

Recall, cf. Subsection 2.2, that $S=\sum_{l\geqslant 1}\gamma_{l1}t^l$, where $\gamma_{l1}\in W_M(k)$ and $\gamma_{l1}l=0$. Let $l=l'p^a$ with $\gcd(l',p)=1$. Then $\gamma_{l1}\in p^{M-a}W_M(k)$.

With the above notation we have in $W_M(k)[\![t]\!]$,

$$E(1,S)^l=\exp(p^aS+\dots+pS^{p^{a-1}})^{l'}E(1,S^{p^a})^{l'}\equiv 1 \bmod (p^a,S^p).$$

Therefore (use that $\gamma_{l1}p^a=0$),

$$S(h(t))\equiv S(tE(1,S))\equiv\sum_l\gamma_{l1}t^lE(1,S)^l\equiv\sum_l\gamma_{l1}t^l=S \bmod S^p\,,$$

and $h^{n+1}(t)\equiv tE(1,S)E(n,S)\equiv tE(n+1,S)\bmod \mathrm{m}(\mathcal{K})S^p$ (use that $S(h(t))^p\equiv 0\bmod S^p$). □

3.2. Specification of lifts $h_{<p}$

Note that $h(t)=t\alpha^{p^{M-1}}$, where $\alpha=E(1,S_0)^p$, and therefore, h commutes with σ, cf. Remark in Subsection 1.1. Now suppose that $h_{<p,0}\in\operatorname{Aut}\mathcal{K}_{<p}$ is a lift of h_0. Then Proposition 1.1 provides us with a unique $h_{<p}\in\operatorname{Aut}O(\mathcal{K}_{<p})$ such that $h_{<p}|_{O(\mathcal{K})}=h$ and $h_{<p}\bmod p=h_{<p,0}$. Therefore, we can work with arbitrary lifts $h_{<p,0}$ of h_0 by working with the appropriate lifts $h_{<p}$ of h. Note that all such lifts $h_{<p}$ commute with σ.

A lift $h_{<p}$ of h can be specified by the formalism of nilpotent Artin–Schreier theory as follows.

- Define similarly to [1] the continuous $W_M(k)$-linear operators $\mathcal{R},\mathcal{S}:\mathcal{L}_{\mathcal{K}}\longrightarrow\mathcal{L}_{\mathcal{K}}$ as follows.
- Suppose $\alpha\in\mathcal{L}_k$.
- For $n>0$, set $\mathcal{R}(t^n\alpha)=0$ and $\mathcal{S}(t^n\alpha)=-\sum_{i\geqslant 0}\sigma^i(t^n\alpha)$.
- For $n=0$, set $\mathcal{R}(\alpha)=\alpha_0(\mathrm{id}_{\mathcal{L}}\otimes\mathrm{Tr})(\alpha)$, $\mathcal{S}(\alpha)=\sum_{0\leqslant j<i<N_0}\sigma^j\alpha_0\,\sigma^i\alpha$, where $\mathrm{Tr}:W_M(k)\longrightarrow W_M(k)$ is induced by the trace map in $k/\mathbb{F}_p$ and $\alpha_0\in W_M(k)$ with $\mathrm{Tr}\alpha_0=1$ was fixed in Subsection 1.4.
- For $n=-n_1p^m$, $\gcd(n_1,p)=1$, set $\mathcal{R}(t^n\alpha)=t^{-n_1}\sigma^{-m}\alpha$ and $\mathcal{S}(t^n\alpha)=\sum_{1\leqslant i\leqslant m}\sigma^{-i}(t^n\alpha)$.

Similarly to [1] we have the following lemma. (We use also the special case $\mathfrak{M}=\mathbb{Z}_p$ of Lemma 2.7.)

Lemma 3.2. — *For any $b\in\mathcal{L}_{\mathcal{K}}$,*

(a) *$b=\mathcal{R}(b)+(\sigma-\mathrm{id}_{\mathcal{L}_{\mathcal{K}}})\mathcal{S}(b)$;*

(b) *if $b=b_1+\sigma c-c$, where $b_1\in\sum_{a\in\mathbb{Z}^+(p)}t^{-a}\mathcal{L}_k+\alpha_0\mathcal{L}$ and $c\in\mathcal{L}_{\mathcal{K}}$ then $\mathcal{R}(b)=b_1$ and $c-\mathcal{S}(b)\in\mathcal{L}$;*

(c) *for any $n\geqslant 0$, $\mathcal{R}$ and $\mathcal{S}$ map $S^{-n}\mathcal{L}_{\mathrm{m}(\mathcal{K})}$ to itself.*

According to Subsection 1.6, for the lift $h_{<p}\in \operatorname{Aut} O(\mathcal{K}_{<p})$ of h (which is attached to the lift $h_{<p,0}$ of h_0), we have that

$$h_{<p}(f)=c\circ (A\otimes \mathrm{id}_{O(\mathcal{K}_{<p})})f\,.$$

Here $c\in \mathcal{L}_{\mathcal{K}}$ and $A=\operatorname{Ad} h_{<p}\in \operatorname{Aut}\mathcal{L}$ (cf. Subsection 1.6 for the definition of $\operatorname{Ad} h_{<p}$). Similarly to [1] it can be proved that the correspondence $h_{<p}\mapsto (c,A)$ is a bijection between the set of all lifts $h_{<p}$ of h and all $(c,A)\in \mathcal{L}_{\mathcal{K}}\times \operatorname{Aut}\mathcal{L}$ such that

$$(\mathrm{id}_{\mathcal{L}}\otimes h)(e)\circ c=(\sigma c)\circ (A\otimes \mathrm{id}_{O(\mathcal{K})})(e)\,. \tag{3.1}$$

This allows us to specify a choice of $h_{<p}$ step by step proceeding from $h_{<p} \bmod C_s(\mathcal{L}_{\mathcal{K}_{<p}})$ to $h_{<p} \bmod C_{s+1}(\mathcal{L}_{\mathcal{K}_{<p}})$ where $1\leqslant s<p$, as follows.

Suppose c and A are already chosen modulo s-th commutators, i.e. we chose $(c_s,A_s)\in \mathcal{L}_{\mathcal{K}}\times \operatorname{Aut}\mathcal{L}$ satisfying the relation (3.1) modulo $C_s(\mathcal{L}_{\mathcal{K}})$.

Then set $c_{s+1}=c_s+X$ and $A_{s+1}=A_s+\mathcal{A}$, where $X\in C_s(\mathcal{L}_{\mathcal{K}})$ and $\mathcal{A}\in \operatorname{Hom}(\mathcal{L},C_s(\mathcal{L}))$. Then (3.1) implies that (here $\mathcal{A}_k=\mathcal{A}\otimes W_M(k)$)

$$\begin{aligned}\sigma X-X+\sum_{a\in\mathbb{Z}^0(p)} t^{-a}\mathcal{A}_k(D_{a0})&\\ \equiv (\mathrm{id}_{\mathcal{L}}\otimes h)e\circ c_s&-\sigma c_s\circ (A_s\otimes \mathrm{id}_{O(\mathcal{K})})e \bmod C_{s+1}(\mathcal{L}_{\mathcal{K}})\end{aligned} \tag{3.2}$$

Now we can specify c_{s+1} and A_{s+1} by setting $X=\mathcal{S}(B_s)$ and $\sum_{a\in\mathbb{Z}^0(p)} t^{-a}\mathcal{A}_k(D_{a0})=\mathcal{R}(B_s)$, where B_s is the right-hand side of the above recurrent relation. Note that the knowledge of all $\mathcal{A}_k(D_{a0})$ recovers uniquely the values of $\mathcal{A}$ on generators of $\mathcal{L}$ and gives well-defined $A_{s+1}\in \operatorname{Aut}\mathcal{L}$. Clearly, (c_{s+1},A_{s+1}) satisfies the relation (3.1) modulo $C_{s+1}(\mathcal{L}_{\mathcal{K}})$. Finally, we obtain the solution $(c^0,A^0):=(c_p,A_p)$ of (3.1) and can use it to specify uniquely the lift $h^0_{<p}$ of h.

3.3. The group $\widetilde{\mathcal{G}}_h$

Consider the group of all continuous automorphisms of $\mathcal{K}_{<p}$ such that their restriction to $\mathcal{K}$ belongs to the closed subgroup in $\operatorname{Aut}\mathcal{K}$ generated by h_0. These automorphisms admit unique lifts to automorphisms of $O(\mathcal{K}_{<p})$ such that their restriction to $O(\mathcal{K})$ belongs to the subgroup $\langle h\rangle$ of $\operatorname{Aut} O(\mathcal{K})$ generated by h, cf. the beginning of Subsection 3.2. Denote the group of these lifts by $\widetilde{\mathcal{G}}_h$.

Use the identification η_M from Subsection 1.4 to obtain a natural short exact sequence of profinite p-groups

$$1\longrightarrow G(\mathcal{L})\longrightarrow \widetilde{\mathcal{G}}_h\longrightarrow \langle h\rangle\longrightarrow 1 \tag{3.3}$$

For any $s \geqslant 2$, the s-th commutator subgroup $C_s(\widetilde{\mathcal{G}}_h)$ is a normal subgroup in $G(\mathcal{L})$. Therefore, $\mathcal{L}_h(s) := C_s(\widetilde{\mathcal{G}}_h)$ is a Lie subalgebra of $\mathcal{L}$. Set $\mathcal{L}_h(1) = \mathcal{L}$. Clearly, for any $s_1, s_2 \geqslant 1$, $[\mathcal{L}_h(s_1), \mathcal{L}_h(s_2)] \subset \mathcal{L}_h(s_1 + s_2)$, in other words, the filtration $\{\mathcal{L}_h(s)\}_{s \geqslant 1}$ is central.

Theorem 3.3. — *For all $s \in \mathbb{N}$, $\mathcal{L}_h(s) = \mathcal{L}(s)$.*

Proof. — Use the notation from Subsection 2.5. Obviously, we have:

- $\mathcal{L}(s+1) = (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)} + \mathcal{L}(s+1) \cap C_2(\mathcal{L})$, where the $W_M(k)$-module $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}$ is generated by all $V_{(b,m)}$ with $m \geqslant s+1$ (for the definition of $V_{(b.m)}$ cf. Proposition 2.6) and $\mathcal{L}(s+1) \cap C_2(\mathcal{L}) = \sum_{s_1+s_2=s+1} [\mathcal{L}(s_1), \mathcal{L}(s_2)]$;
- $\mathcal{L}_h(s+1)$ is the ideal in $\mathcal{L}$ generated by $[\mathcal{L}_h(s), \mathcal{L}]$ and all elements of the form $(\mathrm{Ad} h_{<p}) l \circ (-l)$, where $l \in \mathcal{L}_h(s)$ and $h_{<p}$ is a lift of h.

Consider the elements $V_{(0)}$ and $V_{(b,m),i}$ introduced in the end of Section 2). Recall that $m \in \mathbb{N}$, $1 \leqslant b < e^*$ and $\gcd(b,p) = 1$.

Lemma 3.4. — *There is a lift $h^1_{<p}$ such that if $(\mathrm{Ad} h^1_{<p}) V_{(0)} = \widetilde{V}_{(0)}$ and for all b, m, i, $(\mathrm{Ad} h^1_{<p}) V_{(b,m),i} = \widetilde{V}_{(b,m),i}$ then*

(a) $\widetilde{V}_{(0)} \equiv V_{(0)} \bmod C_2(\mathcal{L})$;
(b) $\widetilde{V}_{(b,m),i} \equiv V_{(b,m),i} + b V_{(b,m+1),i} \bmod (\mathcal{L}(m+2) + \mathcal{L}(m+1) \cap C_2(\mathcal{L}))$.

We shall prove this Lemma below.

Note the following immediate applications of this lemma:

(a) if $l \in \mathcal{L}(s)$ then $(\mathrm{Ad} h^1_{<p}) l \circ (-l) \in \mathcal{L}(s+1)$;
(b) if $l \in (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s+1)}$ then there is an $l' \in (\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s)}$ such that $(\mathrm{Ad} h^1_{<p}) l' \circ (-l') \equiv l \bmod \mathcal{L}(s+1) \cap C_2(\mathcal{L})$.

Now we can finish the proof of our theorem.

Clearly, $\mathcal{L}_h(1) = \mathcal{L}(1)$.

Suppose $s_0 \geqslant 1$ and for $1 \leqslant s \leqslant s_0$, we have $\mathcal{L}_h(s) = \mathcal{L}(s)$.

Then $[\mathcal{L}_h(s_0), \mathcal{L}] = [\mathcal{L}(s_0), \mathcal{L}(1)] \subset \mathcal{L}(s_0+1)$ and applying (a) we obtain that $\mathcal{L}_h(s_0+1) \subset \mathcal{L}(s_0+1)$.

In the opposite direction, note that by inductive assumption,

$$\mathcal{L}(s_0+1) \cap C_2(\mathcal{L}) = \sum_{s_1+s_2=s_0+1} [\mathcal{L}_h(s_1), \mathcal{L}_h(s_2)] \subset \mathcal{L}_h(s_0+1)$$

and then from (b) we obtain that $(\mathcal{K}^*/\mathcal{K}^{*p^M})^{(s_0+1)} \subset \mathcal{L}_h(s_0+1)$. So, $\mathcal{L}(s_0+1) \subset \mathcal{L}_h(s_0+1)$. The theorem is completely proved. □

Proof of Lemma 3.4. — Let

$$\tilde{e}^{\dagger} := (\mathrm{Ad} h^1_{<p} \otimes \mathrm{id}_{O(\mathcal{K})}) e^{\dagger} = \sum_{i,b,m} \frac{t^b}{S^m} \beta_i \widetilde{V}_{(b,m),i} + \alpha_{(0)} \widetilde{V}_{(0)} .$$

Similarly to Subsection 3.2 there is $c^1 \in \mathcal{L}_{\mathcal{K}}$ such that

$$(\mathrm{id}_{\mathcal{L}} \otimes h) e^{\dagger} \circ c^1 = (\sigma c^1) \circ \tilde{e}^{\dagger} , \tag{3.4}$$

and the choice of $h^1_{<p}$ can be specified by an analog of the recurrent procedure from the end of Subsection 3.2.

Namely, set $c^1_1 = 0$ and $A^1_1 = \mathrm{id}_{\mathcal{L}}$. Then for $1 \leqslant s < p$, (c^1_{s+1}, A^1_{s+1}) can be defined as follows:

- $B_s = (\mathrm{id}_{\mathcal{L}} \otimes h) e^{\dagger} \circ c^1_s - (\sigma c^1_s) \circ (A^1_s \otimes \mathrm{id}_{\mathcal{K}}) e^{\dagger}$
- $X_s = \mathcal{S}(B_s)$, $(\mathcal{A}_s \otimes \mathrm{id}_{\mathcal{K}}) e^{\dagger} = \mathcal{R}(B_s)$;
- $c^1_{s+1} = c^1_s + X_s$, $A^1_{s+1} = A^1_s + \mathcal{A}_s$

This gives the system of compatible on $1 \leqslant s \leqslant p$ solutions $(c^1_s, A^1_s) \in \mathcal{L}_{\mathcal{K}} \times \mathrm{Aut}\,\mathcal{L}$ of (3.4) modulo $C_s(\mathcal{L}_{\mathcal{K}})$ and $(c^1, A^1) := (c^1_p, A^1_p)$ defines $h^1_{<p}$.

Let

$$\widetilde{\mathcal{N}}^{(2)} := \sum_{i \geqslant 2} S^{-i} (\mathcal{L}(i) \cap C_2(\mathcal{L}))_{\mathrm{m}(\mathcal{K})} \subset \mathcal{N}^{(2)} .$$

Note that $[\mathcal{N}, \mathcal{N}] \subset \widetilde{\mathcal{N}}^{(2)}$. Consider the following properties.

(1) $(\mathrm{id}_{\mathcal{L}} \otimes h)(e^{\dagger}) = e^{\dagger} + e^+_1 + e^-_1 \bmod S^2\mathcal{N}$, where $e^+_1, e^-_1 \in S\mathcal{N}$ and

$$e^-_1 = \sum_{i,b,m} \frac{bt^b}{S^m} \beta_i V_{(b,m+1),i}, \quad e^+_1 = \sum_{b,i} bt^b \beta_i V_{(b,1),i}$$

(use that $h(S) \equiv S(h(t)) \equiv S \bmod S^p$, cf. the proof of Proposition 3.1).

(2) $\tilde{e}^{\dagger} \equiv e^{\dagger} \bmod S\mathcal{N}$ and $c^1 \in S\mathcal{N}$ (use that for all s, $B_s \in S\mathcal{N}$ and $\mathcal{R}$ and $\mathcal{S}$ map $S\mathcal{N}$ to itself).

(3) $(-\sigma c^1) \circ (\mathrm{id}_{\mathcal{L}} \otimes h)(e^{\dagger}) \circ c^1 \equiv (c^1 - \sigma c^1) + e^{\dagger} + e^{\dagger}_1 \bmod S^2\mathcal{N} + S\widetilde{\mathcal{N}}^{(2)}$ (use that $c \in S\mathcal{N}$ and $(\mathrm{id}_{\mathcal{L}} \otimes h)(e^{\dagger}) \in \mathcal{N}$)

(4) Apply $\mathcal{R}$ to the congruence from c), use that $S^2\mathcal{N} + S\widetilde{\mathcal{N}}^{(2)}$ is mapped by $\mathcal{R}$ to itself and $\mathcal{R}(c^1 - \sigma c^1) = \mathcal{R}(e^+_1) = 0$

$$\tilde{e}^{\dagger} \equiv \sum_{i,b,m} \frac{t^b}{S^m} \beta_i \left(V_{(b,m),i} + b V_{(b,m+1),i} \right) + \alpha_0 V_{(0)} \bmod S^2\mathcal{N} + S\widetilde{\mathcal{N}}^{(2)} .$$

It remains to note that the last congruence is equivalent to the statement of our lemma. □

3.4. The group $\mathcal{G}_h$

Let $\mathcal{G}_h = \widetilde{\mathcal{G}}_h/\widetilde{\mathcal{G}}_h^{p^M} C_p(\widetilde{\mathcal{G}}_h)$.

Proposition 3.5. — *Exact sequence* (3.3) *induces the following exact sequence of p-groups*

$$1 \longrightarrow G(\mathcal{L})/G(\mathcal{L}(p)) \longrightarrow \mathcal{G}_h \longrightarrow \langle h\rangle \operatorname{mod} \langle h^{p^M}\rangle \longrightarrow 1 \tag{3.5}$$

Proof. — Set

$$\mathcal{M} := \mathcal{N} + \mathcal{L}(p)_{\mathcal{K}} = \sum_{1\leqslant s<p} S^{-s}\mathcal{L}(s)_{\mathrm{m}(\mathcal{K})} + \mathcal{L}(p)_{\mathcal{K}}$$

$$\mathcal{M}_{<p} := \sum_{1\leqslant s<p} S^{-s}\mathcal{L}(s)_{\mathrm{m}(\mathcal{K}_{<p})} + \mathcal{L}(p)_{\mathcal{K}_{<p}}$$

where $\mathrm{m}(\mathcal{K}_{<p}) = W_M(\mathrm{m}_{<p}) \cap O(\mathcal{K}_{<p})$ and $\mathrm{m}_{<p}$ is the maximal ideal of the valuation ring of $\mathcal{K}_{<p}$.

Then $\mathcal{M}$ has the induced structure of Lie $W_M(k)$-algebra (use the Lie bracket from $\mathcal{L}_{\mathcal{K}}$) and $S^{p-1}\mathcal{M}$ is an ideal in $\mathcal{M}$. Similarly, $\mathcal{M}_{<p}$ is a Lie $W_M(k)$-algebra (containing $\mathcal{M}$ as its subalgebra) and $S^{p-1}\mathcal{M}_{<p}$ is an ideal in $\mathcal{M}_{<p}$. Note that $e \in \mathcal{M}$, $f \in \mathcal{M}_{<p}$, $S^{p-1}\mathcal{M}_{<p} \cap \mathcal{M} = S^{p-1}\mathcal{M}$, and we have a natural embedding of $\bar{\mathcal{M}} := \mathcal{M}/S^{p-1}\mathcal{M}$ into $\bar{\mathcal{M}}_{<p} := \mathcal{M}_{<p}/S^{p-1}\mathcal{M}_{<p}$. For $i \geqslant 0$, we have also $(\mathrm{id}_{\mathcal{L}} \otimes h - \mathrm{id}_{\mathcal{M}})^i\mathcal{M} \subset S^i\mathcal{M}$.

Consider the orbit of $\bar{f} := f \operatorname{mod} S^{p-1}\mathcal{M}_{<p}$ with respect to the natural action of $\widetilde{\mathcal{G}}_h \subset \operatorname{Aut} O(\mathcal{K}_{<p})$ on $\bar{\mathcal{M}}_{<p}$. Prove that the stabilizer $\mathcal{H}$ of $\bar{f}$ equals $\widetilde{\mathcal{G}}_h^{p^M} C_p(\widetilde{\mathcal{G}}_h)$.

If $l \in G(\mathcal{L})$ then $\eta_M^{-1}(l) \in \mathcal{G}_{<p}$ sends f to $f \circ l$. This means that for $l \in \mathcal{L} \cap \mathcal{H}$ we have

$$l \in S^{p-1}\mathcal{M}_{<p} \cap \mathcal{L} = S^{p-1}\mathcal{M} \cap \mathcal{L} = \mathcal{L}(p)_{\mathcal{K}} \cap \mathcal{L} = \mathcal{L}(p) = C_p(\widetilde{\mathcal{G}}_h)\,.$$

Therefore, $\mathcal{H} \cap G(\mathcal{L}) = C_p(\widetilde{\mathcal{G}}_h) \subset \mathcal{H}$ and we obtain the embedding

$$\kappa : G(\mathcal{L})/G(\mathcal{L}(p)) \longrightarrow \widetilde{\mathcal{G}}_h/\mathcal{H}\,.$$

Now consider the lift $h^0_{<p}$ from the end of Subsection 3.2.

Note that $\widetilde{\mathcal{G}}_h^{p^M} \operatorname{mod} C_p(\widetilde{\mathcal{G}}_h)$ is generated by $h^{0p^M}_{<p}$. Indeed, any finite p-group of nilpotent class $< p$ is P-regular, cf. [10] Subsection 12.3. In particular, for any $g \in G(\mathcal{L})$, $(h^0_{<p} \circ g)^{p^M} \equiv h^{0p^M}_{<p} \circ g' \operatorname{mod} C_p(\widetilde{\mathcal{G}}_h)$, where g' is the product of p^M-th powers of elements from $G(\mathcal{L})$, but $G(\mathcal{L})$ has period p^M.

As earlier, $h^0_{<p}f = c^0 \circ (A^0 \otimes \mathrm{id}_{\mathcal{K}})f$. Note that $c^0 \in S\mathcal{M}$ (proceed similarly to the proof of Lemma 3.4(b)).

Then

$$h^{0p^M}_{<p}(f)$$
$$= (\mathrm{id}\otimes h)^{p^M-1}\left(c^0\circ(A^0\otimes h^{-1})c^0\circ\dots\circ(A^0\otimes h^{-1})^{p^M-1}c^0\right)$$
$$\circ\,(A^{0p^M}\otimes\mathrm{id})f\,.$$

Clearly, $(A^0-\mathrm{id}_{\mathcal{L}})^p\mathcal{L}\subset\mathcal{L}(p)$ and, therefore, $(A^{0p^M}\otimes\mathrm{id})\bar{f}=\bar{f}$.

Similarly, $B=A^0\otimes h^{-1}$ is an automorphism of the Lie algebra $\mathcal{M}$, and for all $s\geqslant 0$, $(B-\mathrm{id}_{\mathcal{M}})(S^s\mathcal{M})\subset S^{s+1}\mathcal{M}$.

Lemma 3.6. — *For any $m\in\mathcal{SM}$, $m\circ B(m)\circ\dots\circ B^{p^M-1}m\in\mathcal{S}^p\mathcal{M}$.*

Proof. — Consider the Lie algebra $\mathfrak{M}=S\mathcal{M}/S^p\mathcal{M}$ with the filtration $\{\mathfrak{M}(i)\}_{i\geqslant 1}$ induced by the filtration $\{S^i\mathcal{M}\}_{i\geqslant 1}$. This filtration is central, i.e. for any $i,j\geqslant 1$, $[\mathfrak{M}(i),\mathfrak{M}(j)]\subset\mathfrak{M}(i+j)$. In particular, the nilpotent class of $\mathfrak{M}$ is $<p$.

The operator B induces the operator on $\mathfrak{M}$ which we denote also by B. Clearly, $B=\widetilde{\exp}\,\mathcal{B}$ where $\mathcal{B}$ is a differentiation on $\mathfrak{M}$ such that for all $i\geqslant 1$, $\mathcal{B}(\mathfrak{M}(i))\subset\mathfrak{M}(i+1)$.

Let $\widetilde{\mathfrak{M}}$ be a semi-direct product of $\mathfrak{M}$ and the trivial Lie algebra $(\mathbb{Z}/p^M)w$ via $\mathcal{B}$. This means that $\widetilde{\mathfrak{M}}=\mathfrak{M}\oplus(\mathbb{Z}/p^M)w$ as $\mathbb{Z}/p^M$-module, $\mathfrak{M}$ and $(\mathbb{Z}/p^M)w$ are Lie subalgebras of $\widetilde{\mathfrak{M}}$ and for any $m\in\mathfrak{M}$, $[m,w]=\mathcal{B}(m)$. Clearly, $C_2(\widetilde{\mathfrak{M}})=[\widetilde{\mathfrak{M}},\widetilde{\mathfrak{M}}]\subset\mathfrak{M}(2)$. This implies that $\widetilde{\mathfrak{M}}$ has nilpotent class $<p$ and we can consider the p-group $G(\widetilde{\mathfrak{M}})$. This group has nilpotent class $<p$ and period p^M (because for any $\bar{m}\in\widetilde{\mathfrak{M}}$, its p^M-th power in $G(\widetilde{\mathfrak{M}})$ equals $p^M\bar{m}=0$).

Note that the conjugation by w in $G(\widetilde{\mathfrak{M}})$ is given by the automorphism $\widetilde{\exp}\,\mathcal{B}=B$. Indeed, if $m\in\mathfrak{M}$ then

$$B(m)=(\widetilde{\exp}\mathcal{B})m=\sum_{0\leqslant n<p}\mathcal{B}^n(m)/n!=(-w)\circ m\circ w$$

(use very well-known formula in a free associative algebra $\mathbb{Q}[\![X,Y]\!]$,

$$\exp(-Y)\exp(X)\exp(Y)=\exp(X+\ldots+(\mathrm{ad}^{\,n}Y)X/n!+\ldots)\,,$$

where $\mathrm{ad}\,Y:X\mapsto[X,Y]$).

In particular, for any element $\bar{m}=m\,\mathrm{mod}\,\mathcal{N}(p)\in\mathfrak{M}$, we have $w_1\circ\bar{m}=B(\bar{m})\circ w_1$, where $w_1=-w$. Therefore, $0=(\bar{m}\circ w_1)^{p^M}=\bar{m}\circ B(\bar{m})\circ\dots\circ B^{p^M-1}(\bar{m})\circ w_1^{p^M}$, and it remains to note that $w_1^{p^M}=0$. □

Applying the above Lemma we obtain that

$$c^0\circ(A^0\otimes h^{-1})c^0\circ\dots\circ(A^0\otimes h^{-1})^{p^M-1}c^0\in\mathcal{N}(p)\subset S^{p-1}\mathcal{M}$$

and, therefore, $h_{<p}^{0p^M}(\bar{f})=0$.

Thus, we proved that $\widetilde{\mathcal{G}}_h^{p^M}C_p(\widetilde{\mathcal{G}}_h)\subset\mathcal{H}$.

Suppose $g=h_{<p}^m l\in\mathcal{H}$ with some $l\in G(\mathcal{L})$. Then $g(f)=b\circ f$ where $b\in S^{p-1}\mathcal{M}_{<p}$. Note that $\sigma(b)\in S^{p-1}\mathcal{M}_{<p}$. Then

$$g(e)\circ b\circ f=g(e)\circ g(f)=g(\sigma f)=\sigma b\circ\sigma f=\sigma b\circ e\circ f$$

implies that $g(e)\equiv e\,\mathrm{mod}\,S^{p-1}\mathcal{M}$. Thus $(\mathrm{id}\otimes h)^m(e)\equiv e\,\mathrm{mod}\,S^{p-1}\mathcal{M}$.

Now use that $e\equiv e^\dagger\,\mathrm{mod}\,\mathcal{L}_{\mathrm{m}(\mathcal{K})}+C_2(\mathcal{L})_{\mathcal{K}}$, cf. the beginning of the proof of Proposition 2.6.

Clearly, $\mathcal{L}_{\mathrm{m}(\mathcal{K})}+\mathcal{L}(p)_{\mathcal{K}}\supset S^{p-1}\mathcal{M}$ and, therefore, for the element

$$e_{<p}^\dagger:=\sum_{i,b}\sum_{1\leqslant m<p}\frac{t^b}{S^m}\beta_i V_{(b,m),i}$$

we obtain $(\mathrm{id}_{\mathcal{L}}\otimes h)^m(e_{<p}^\dagger)\equiv e_{<p}^\dagger\,\mathrm{mod}\,\mathcal{L}_{\mathrm{m}(\mathcal{K})}+C_2(\mathcal{L}_{\mathcal{K}})$. But

$$h^m(e_{<p}^\dagger)\equiv\sum_{i,b}\sum_{1\leqslant m<p}\frac{t^bE(bm,S)}{S^m}\beta_i V_{(b,m),i}\,\mathrm{mod}\,\mathcal{L}_{\mathrm{m}(\mathcal{K})}+\mathcal{L}(p)_{\mathcal{K}}$$

Now following the coefficients for $V_{(b,p-2),i}$ we obtain $m\equiv 0\,\mathrm{mod}\,p^M$. Therefore, $l\in\mathcal{H}\cap G(\mathcal{L})=C_p(\widetilde{\mathcal{G}}_h)$ and $\mathcal{H}\subset\widetilde{\mathcal{G}}_h^{p^M}C_p(\widetilde{\mathcal{G}}_h)$.

Finally, we have $\widetilde{\mathcal{G}}_h/\mathcal{H}=\mathcal{G}_h$, $\mathcal{H}\,\mathrm{mod}\,C_p(\widetilde{\mathcal{G}}_h)=\langle h_{<p}^{p^M}\rangle$ and, therefore, $\mathrm{Coker}\,\kappa=\langle h\rangle\,\mathrm{mod}\,\langle h^{p^M}\rangle$. □

Corollary 3.7. — *If L_h is a Lie $\mathbb{Z}/p^M$ algebra such that $\mathcal{G}_h=G(L_h)$ then* (3.5) *induces the following short exact sequence of Lie $\mathbb{Z}/p^M$-algebras*

$$0\longrightarrow\mathcal{L}/\mathcal{L}(p)\longrightarrow L_h\longrightarrow(\mathbb{Z}/p^M)h\longrightarrow 0$$

Remark. — In [1] we studied the structure of the above Lie algebra L_h in the case $M=1$. The case of arbitrary M will be considered in a forthcoming paper.

3.5. Ramification estimates

Use the identification from Subsection 1.3, $\eta_M:\mathrm{Gal}(\mathcal{K}_{<p}/\mathcal{K})=\mathcal{G}_{<p}\simeq G(\mathcal{L})$ and set for all for $s\in\mathbb{N}$, $\mathcal{K}[s,M]:=\mathcal{K}_{<p}^{G(\mathcal{L}(s+1))}$. Denote by $v(s,M)$ the maximal upper ramification number of the extension $\mathcal{K}[s,M]/\mathcal{K}$. In other words,

$$v(s,M)=\max\{v\mid\mathcal{G}_{<p}^{(v)}\text{ acts non-trivially on }\mathcal{K}[s,M]\}\,.$$

PROPOSITION 3.8. — *For all* $s \in \mathbb{N}$, $v(s, M) = p^{M-1}(e^* s - 1)$ *(for the definition of* e^* *cf, Subsection 2.1).*

Proof. — Recall, cf. Subsection 1.7, that for any $v \geqslant 0$, the ramification subgroups $\mathcal{G}_{<p}^{(v)}$ are identified with the ideals $\mathcal{L}^{(v)}$ of $\mathcal{L}$, and for sufficiently large $N = N(v)$, the ideal $\mathcal{L}_k^{(v)}$ is generated by all $\sigma^n \mathcal{F}^0_{\gamma,-N}$, where $\gamma \geqslant v$, $n \in \mathbb{Z}/N_0$ and the elements $\mathcal{F}^0_{\gamma,-N}$ are given by (1.3).

Let $e^0 = e^*(1 - 1/p)$.

LEMMA 3.9. — *If* $a \in \mathbb{Z}^+(p)$, $u \in \mathbb{N}$ *and* $0 \leqslant c < M$ *then the following two conditions are equivalent:*

(a) $t^a S^{-u} \in \mathrm{m}(\mathcal{K}) \bmod p^c\, O(\mathcal{K})$;

(b) $a > e^* u + e^0(c - 1)$.

Proof of Lemma 3.9. — Proposition 2.1(c) implies that

$$t^a S^{-u} = t^{a-ue^*} \eta_0 \left(1 + \sum_{i \geqslant 1} t^{-ie^0} \eta_i(u) p^i\right)$$

where η_0 and all $\eta_i(u)$ are invertible elements of $W_M(k)[\![t]\!] \subset O(\mathcal{K})$. Therefore, $t^a S^{-u} \in \mathrm{m}(\mathcal{K}) \bmod p^c O(\mathcal{K})$ if and only if for all $1 \leqslant i < c$, $t^{a-ue^*-ie^0} \in \mathrm{m}(\mathcal{K})$, i.e. $a - ue^* - (c-1)e^0 > 0$. The lemma is proved. □

COROLLARY 3.10. — $D_{an} \in \mathcal{L}(u)_k \bmod p^c O(\mathcal{K})$ *if and only if we have that* $a \geqslant e^*(u - 1) + (c - 1)e^0 + 1$.

LEMMA 3.11. — *Suppose* $N \geqslant 0$.

(a) *If* $\gamma > p^{M-1}(e^* s - 1)$ *then* $\mathcal{F}^0_{\gamma,-N} \in \mathcal{L}(s+1)_k$*;*

(b) *if* $\gamma = p^{M-1}(e^* s - 1)$ *then*

$$\mathcal{F}^0_{\gamma,-N} \equiv p^{M-1} D_{e^* s-1, M-1} \bmod \mathcal{L}(s+1)_k \, .$$

Proof of Lemma 3.11. — For any $\gamma > 0$, $\mathcal{F}^0_{\gamma,-N}$ is a $\mathbb{Z}/p^M$-linear combination of the monomials of the form

$$X(b\,; a_1, \ldots, a_r; m_2, \ldots, m_r) = p^b a_1 [\ldots [D_{a_1, b-m_1}, D_{a_2, b-m_2}], \ldots, D_{a_r, b-m_r}] \, ,$$

where $0 \leqslant b < M$, $1 \leqslant r < p$, all $a_i \in \mathbb{Z}^0(p)$, $0 = m_1 \leqslant m_2 \leqslant \cdots \leqslant m_r$, and

$$p^b \left(a_1 + \frac{a_2}{p^{m_2}} + \cdots + \frac{a_r}{p^{m_r}}\right) = \gamma \, .$$

For $1 \leqslant i \leqslant r$, let $u_i \in \mathbb{Z}$ be such that (note that $p^M | e^*$, $p^{M-1} | e^0$ and if $M = 1$ then $M - b - 1 = 0$)

$$1 + e^*(u_i - 1) + e^0(M - b - 1) \leqslant a_i < e^* u_i + e^0(M - b - 1) \, .$$

This means that all $D_{a_i,b-m_i} \in \mathcal{L}(u_i)_k \bmod p^{M-b}\mathcal{L}_k$.

Suppose $X(b\,;a_1,\dots,a_r;m_2,\dots,m_r) \notin \mathcal{L}(s+1)_k$. This implies that $u_1+\dots+u_r \leqslant s$ and, therefore, $a_1+\dots+a_r \leqslant e^*s+re^0(M-b-1)-r$.

If $\gamma > p^{M-1}(e^*s-1)$ then $a_1+\dots+a_r > p^{M-b-1}(e^*s-1)$ and

$$e^*s+re^0(M-b-1)-r > p^{M-b-1}(e^*s-1).$$

Set $c=M-b-1$, then $0\leqslant c<M$ and

$$(p^c-1)(e^*s-1)\leqslant r(e^0c-1)\,.$$

If $c=0$ then $r\leqslant 0$, contradiction.

If $c\geqslant 1$ then (use that $r\leqslant p-1$ and $s\geqslant 1$)

$$(1+p+\dots+p^{c-1})(e^*-1)\leqslant e^0c-1\,.$$

But then $e^*=e^0(1+1/(p-1))\geqslant e^0+1$ implies that $1+p+\dots+p^{c-1}<c$. This contradiction proves (a).

Suppose $\gamma=p^{M-1}(e^*s-1)$. Then the expression for $\mathcal{F}^0_{\gamma,-N}$ contains the term $p^{M-1}D_{e^*s-1,M-1}$. Take (with above notation) any another monomial $X(b;a_1,\dots,a_r;m_2,\dots,m_r)$ from the expression of $\mathcal{F}^0_{\gamma,-N}$. Clearly, $r\geqslant 2$. As earlier, the assumption that this monomial does not belong to $\mathcal{L}(s+1)_k$ implies that

$$(p^c-1)(e^*s-1)\leqslant r(e^0c-1)+1\,.$$

If $c=0$ then $r\leqslant 1$, contradiction.

If $c\geqslant 1$ then again use that $r\leqslant p-1$ to obtain

$$(1+p+\dots+p^{c-1})(e^*s-1)\leqslant e^0c-1+1/(p-1)<e^0c$$

and note that the left-hand side of this inequality $>ce^0$ (use that $e^*s-1\geqslant e^*-1\geqslant e^0$). The contradiction. The lemma is completely proved. ☐

It remains to note that Lemma 3.11 implies that

$$\max\{v\mid \mathcal{L}^{(v)}\not\subset\mathcal{L}(s+1)\}=p^{M-1}(e^*s-1)\,.$$

Proposition 3.8 is completely proved. ☐

4. Applications to the mixed characteristic case

Let K be a finite field extension of $\mathbb{Q}_p$ with the residue field $k\simeq\mathbb{F}_{p^{N_0}}$ and the ramification index e_K. Let π_0 be a uniformising element in K. Denote by $\bar K$ an algebraic closure of K and set $\Gamma=\mathrm{Gal}(\bar K/K)$. Assume that K contains a primitive p^M-th root of unity ζ_M.

4.1. The subgroup $\widetilde{\Gamma}$

For $n\in\mathbb{N}$, choose $\pi_n\in\bar{K}$ such that $\pi_n^p=\pi_{n-1}$. Let $\widetilde{K}=\bigcup_{n\in\mathbb{N}}K(\pi_n)$, $\Gamma_{<p}:=\Gamma/\Gamma^{p^M}C_p(\Gamma)$ and $\widetilde{\Gamma}=\mathrm{Gal}(\bar{K}/\widetilde{K})$. Then $\widetilde{\Gamma}\subset\Gamma$ induces a continuous group homomorphism $i:\widetilde{\Gamma}\longrightarrow\Gamma_{<p}$.

We have $\mathrm{Gal}(K(\pi_M)/K)=\langle\tau_0\rangle^{\mathbb{Z}/p^M}$, where $\tau_0(\pi_M)=\pi_M\zeta_M$. Let $j:\Gamma_{<p}\longrightarrow\mathrm{Gal}(K(\pi_M)/K)$ be a natural epimorphism.

Proposition 4.1. — *The following sequence*

$$\widetilde{\Gamma}\xrightarrow{i}\Gamma_{<p}\xrightarrow{j}\langle\tau_0\rangle^{\mathbb{Z}/p^M}\longrightarrow 1$$

is exact.

Proof. — For $n>M$, let $\zeta_n\in\bar{K}$ be such that $\zeta_n^p=\zeta_{n-1}$.

Consider $\widetilde{K}'=\bigcup_{n\geqslant M}K(\pi_n,\zeta_n)$. Then $\widetilde{K}'/K$ is Galois with the Galois group $\Gamma_{\widetilde{K}'/K}=\langle\sigma,\tau\rangle$. Here for any $n\geqslant M$ and some $s_0\in\mathbb{Z}$, $\sigma\zeta_n=\zeta_n^{1+p^Ms_0}$, $\sigma\pi_n=\pi_n$, $\tau(\zeta_n)=\zeta_n$, $\tau\pi_n=\pi_n\zeta_n$ and $\sigma^{-1}\tau\sigma=\tau^{(1+p^Ms_0)^{-1}}$.

Therefore, $\Gamma_{\widetilde{K}'/K}^{p^M}=\langle\sigma^{p^M},\tau^{p^M}\rangle$ and for the subgroup of second commutators we have $C_2(\Gamma_{\widetilde{K}'/K})\subset\langle\tau^{p^M}\rangle\subset\Gamma_{\widetilde{K}'/K}^{p^M}$. This implies that

$$\Gamma_{\widetilde{K}'/K}^{p^M}C_p(\Gamma_{\widetilde{K}'/K})=\langle\sigma^{p^M},\tau^{p^M}\rangle$$

and for $\Gamma_{\widetilde{K}'/K}(M):=\Gamma_{\widetilde{K}'/K}/\Gamma_{\widetilde{K}'/K}^{p^M}C_p(\Gamma_{\widetilde{K}'/K})$, we obtain a natural exact sequence

$$\langle\sigma\rangle\longrightarrow\Gamma_{\widetilde{K}'/K}(M)\longrightarrow\langle\tau\rangle\,\mathrm{mod}\,\langle\tau^{p^M}\rangle=\langle\tau_0\rangle^{\mathbb{Z}/p^M}\longrightarrow 1\,.$$

Note that $\Gamma_{\widetilde{K}'}$ together with a lift $\hat{\sigma}\in\widetilde{\Gamma}$ of σ generate $\widetilde{\Gamma}$. The above short exact sequence implies that $\mathrm{Ker}\left(\Gamma_{<p}\longrightarrow\langle\tau_0\rangle^{\mathbb{Z}/p^M}\right)$ is generated by $\hat{\sigma}$ and the image of $\Gamma_{\widetilde{K}'}$. So, this kernel coincides with the image of $\widetilde{\Gamma}$ in $\Gamma_{<p}$. □

4.2. Special choice of S and S_0

Let R be Fontaine's ring. We have a natural embedding $k\subset R$ and an element $t_0=(\pi_n\,\mathrm{mod}\,p)_{n\geqslant 0}\in R$. Then we can identify the field $k((t_0))$ with the field $\mathcal{K}$ from Sections 1-3. If $R_0=\mathrm{Frac}\,R$ then $\mathcal{K}$ is a closed subfield of R_0 and the theory of the field-of-norms functor identifies R_0 with the completion of the separable closure $\mathcal{K}_{sep}$ of $\mathcal{K}$ in R_0. Note that R is the valuation ring of R_0 and denote by m_R the maximal ideal of R.

This allows us to identify $\mathcal{G}=\mathrm{Gal}(\mathcal{K}_{sep}/\mathcal{K})$ with $\widetilde{\Gamma}\subset\Gamma\subset\mathrm{Aut}\,R_0$. This identification is compatible with the appropriate ramification filtrations. Namely, if $\varphi_{\widetilde{K}/K}$ is the Herbrand function of the (arithmetically profinite) field extension $\widetilde{K}/K$ then for any $v\geqslant 0$, $\mathcal{G}^{(v)}=\Gamma^{(v_1)}\cap\widetilde{\Gamma}$, where $v_1=\varphi_{\widetilde{K}/K}(v)$.

Let as earlier, $\mathcal{G}_{<p}=\mathcal{G}/\mathcal{G}^{p^M}C_p(\mathcal{G})$. Then the embedding $\mathcal{G}=\widetilde{\Gamma}\subset\Gamma$ induces a natural continuous morphism ι of the infinite group $\mathcal{G}_{<p}$ to the finite group $\Gamma_{<p}$. Therefore, by Proposition 4.1 we obtain the following exact sequence

$$\mathcal{G}_{<p}\xrightarrow{\iota}\Gamma_{<p}\xrightarrow{j}\langle\tau_0\rangle^{\mathbb{Z}/p^M}\longrightarrow 1\,. \tag{4.1}$$

Let $\zeta_M=1+\sum_{i\geqslant 1}[\beta_i]\pi_0^i$ with all $\beta_i\in k$. Consider the identification of rings $R/t_0^{e_K}\simeq O_{\bar{K}}/p$ given by $(r_0,\dots,r_n,\dots)\mapsto r_0$. If $\varepsilon=(\zeta_n)_{n\geqslant 0}$ is Fontaine's element such that ζ_M is our fixed p^M-th root of unity then we have in $W_M(R)$ the following congruence (as earlier, $t=(t_0,\dots,0)\in W_M(R)$)

$$\sigma^{-M}\varepsilon\equiv 1+\sum_{i\geqslant 1}\beta_i t^i \bmod (t^{e_K},p)\,. \tag{4.2}$$

Now we can specify the choice of the elements $S_0,S\in\mathrm{m}(\mathcal{K})$, cf. Subsection 2.1, by setting $E(1,S_0)=1+\sum_i\beta_i t^i$ and $S=[p]^M(S_0)$. Note that $S \bmod p$ generates the ideal $(t_0^{e^*})$ in $O_{\mathcal{K}}=k[\![t_0]\!]$, where $e^*=pe_K/(p-1)$. Now congruence (4.2) can be rewritten in the following form

$$\sigma^{-M}\varepsilon\equiv E(1,S_0)\bmod(\sigma^{-1}S^{p-1},p)\,.$$

Applying σ we obtain

$$\sigma^{-M+1}\varepsilon\equiv E(1,[p]S_0)\bmod(S^{p-1},p)\,,$$

and then taking p^{M-1}-th power

$$\varepsilon\equiv E(1,S)\bmod S^{p-1}W_M(R)\,.$$

4.3. The lifts $\eta_{<p}$

Let $v_{\mathcal{K}}$ be the extension of the normalized valuation on $\mathcal{K}$ to R_0. Consider a continuous field embedding $\eta_0:\mathcal{K}\longrightarrow R_0$ compatible with $v_{\mathcal{K}}$. Denote by $\mathrm{Iso}(\eta_0,\mathcal{K}_{<p},R_0)$ the set of all extensions $\eta_{<p,0}$ of η_0 to $\mathcal{K}_{<p}$. This set is a principal homogeneous space over $\mathcal{G}_{<p}=G(\mathcal{L})$.

Choose a lift $\eta : O(\mathcal{K}) \longrightarrow W_M(R_0)$ such that $\eta \bmod p = \eta_0$ and $\eta\sigma = \sigma\eta$. Proceeding similarly to Subsection 1.1 we can identify the set of all lifts $\eta_{0,<p}$ of η_0 from $\mathrm{Iso}(\eta_0, \mathcal{K}_{<p}, R_0)$ with the set of all (commuting with σ) lifts $\eta_{<p}$ of η from $\mathrm{Iso}(\eta, O(\mathcal{K}_{<p}), W_M(R_0))$.

Specify uniquely each lift $\eta_{<p}$ by the knowledge of $\eta_{<p}(f) \in \mathcal{L}_{R_0}$ in the set of all solutions $f' \in \mathcal{L}_{R_0}$ of the equation $\sigma f' = \eta(e) \circ f'$. (The elements $e \in \mathcal{L}_{\mathcal{K}}$ and $f \in \mathcal{L}_{\mathcal{K}_{<p}}$ were chosen in Subsection 1.4.)

Consider the appropriate submodules $\mathcal{M} \subset \mathcal{L}_{\mathcal{K}}$, $\mathcal{M}_{<p} \subset \mathcal{L}_{\mathcal{K}_{<p}}$ from Subsection 3.4 and define similarly

$$\mathcal{M}_{R_0} = \sum_{1 \leqslant s < p} S^{-s} \mathcal{L}(s)_{\mathrm{m}(R)} + \mathcal{L}(p)_{R_0} \subset \mathcal{L}_{R_0}\,,$$

where $\mathrm{m}(R) = W_M(\mathrm{m}_R)$. We know that $e \in \mathcal{M}$, $f \in \mathcal{M}_{<p}$ and for similar reasons, all $\eta_{<p}(f) \in \mathcal{M}_{R_0}$.

Lemma 4.2. — *With above notation suppose that*

$$\eta(e) \equiv e \bmod S^{p-1}\mathcal{M}_{R_0}.$$

Then there is $c \in S^{p-1}\mathcal{M}_{R_0}$ such that $\eta(e) = \sigma c \circ e \circ (-c)$.

Proof. — Note that $S^{p-1}\mathcal{M}_{R_0}$ is an ideal in $\mathcal{M}_{R_0}$ and for any $i \in \mathbb{N}$ and $m \in S^{p-1}C_i(\mathcal{M}_{R_0})$, there is $c \in S^{p-1}C_i(\mathcal{M}_{R_0})$ such that $\sigma c - c = m$. (Use that σ is topologically nilpotent on $S^{p-1}C_i(\mathcal{M}_{R_0})$.)

Therefore, there is $c_1 \in S^{p-1}\mathcal{M}_{R_0}$ such that $\eta(e) = e + \sigma c_1 - c_1$. This implies that $\eta(e) \circ c_1 \equiv \sigma c_1 \circ e \bmod S^{p-1}C_2(\mathcal{M}_{R_0})$. Similarly, there is $c_2 \in S^{p-1}C_2(\mathcal{M}_{R_0})$ such that $\eta(e) \circ c_1 + c_2 = \sigma c_2 + \sigma c_1 \circ e_0$ and $\eta(e_0) \circ c_1 \circ c_2 \equiv \sigma c_2 \circ \sigma c_1 \circ e_0 \bmod S^{p-1}C_3(\mathcal{M}_{R_0})$, and so on.

After $p-1$ iterations we obtain for $1 \leqslant i < p$ the elements $c_i \in S^{p-1}C_i(\mathcal{M}_{R_0})$ such that

$$\eta(e) \circ (c_1 \circ \cdots \circ c_{p-1}) = \sigma(c_{p-1} \circ \cdots \circ c_1) \circ e.$$

The lemma is proved. □

The above lemma implies the following properties:

Proposition 4.3.

(a) *If $\eta(e) \equiv e \bmod S^{p-1}\mathcal{M}_{R_0}$ then for any $\eta_{<p} \in \mathrm{Iso}(\eta, \mathcal{K}_{<p}, R_0)$, there is a unique $l \in G(\mathcal{L}) \bmod G(\mathcal{L}(p))$ such that*

$$\eta_{<p}(f) \equiv f \circ l \bmod S^{p-1}\mathcal{M}_{R_0}\,.$$

(b) *Suppose $\eta', \eta'' : O(\mathcal{K}) \longrightarrow W_M(R_0)$ are such that*

$$\eta'(t) \equiv \eta''(t) \bmod S^{p-1}W_M(\mathrm{m}_R)\,.$$

If $\eta'_{<p} \in \mathrm{Iso}(\eta', O(\mathcal{K}_{<p}), W_M(R_0))$ *and* $\eta''_{<p} \in \mathrm{Iso}(\eta'', O(\mathcal{K}_{<p}), W_M(R_0))$ *then there is a unique* $l \in G(\mathcal{L})$ *such that*

$$\eta'_{<p}(f) \equiv \eta''_{<p}(f) \circ l \bmod S^{p-1}\mathcal{M}_{R_0}.$$

4.4. Upper ramification numbers $v(K[s, M]/K)$

The action of $\Gamma = \mathrm{Gal}(\bar{K}/K)$ on R_0 is strict and, therefore, the elements $g \in \Gamma$ can be identified with all continuous field embeddings $g : \mathcal{K}_{sep} \to R_0$ such that $g|_{\mathcal{K}}$ belongs to the set $\langle \tau_0 \rangle = \{\tau_0^a \mid a \in \mathbb{Z}_p\}$.

Extend τ_0 now to a continuous embedding $\tau : O(\mathcal{K}) \longrightarrow W_M(R_0)$ uniquely determined by the condition $\tau(t) = t\varepsilon$. Clearly, τ commutes with σ. Then the results of Subsection 1.1 imply that the elements of Γ are identified with the continuous embeddings $g : O(\mathcal{K}_{sep}) \to W_M(R_0)$ such that $g|_{O(\mathcal{K})}$ belongs to the set $\langle \tau \rangle$.

Consider $h_0 \in \mathrm{Aut}(\mathcal{K})$ such that $h_0(t_0) = t_0 E(1, S \bmod p)$ and $h_0|_k = \mathrm{id}$. Then its lift $h \in \mathrm{Aut} O(\mathcal{K})$ such that $h(t) = tE(1, S)$ commutes with σ and there are the appropriate groups $\widetilde{\mathcal{G}}_h$ and $\mathcal{G}_h$ from Section 3.

Clearly, $h(t) \equiv \tau(t) \bmod S^{p-1}\mathrm{m}_R$ and we can apply Proposition 4.3(b). This implies that the Γ-orbit of $f \bmod S^{p-1}\mathcal{M}_{R_0}$ is contained in the $\widetilde{\mathcal{G}}_h$-orbit of $f \bmod S^{p-1}\mathcal{M}_{R_0}$. Therefore, there is a map of sets $\kappa : \Gamma \longrightarrow \mathcal{G}_h$ uniquely determined by the requirement that for any $g \in \Gamma$,

$$(\mathrm{id}_{\mathcal{L}} \otimes g)f \equiv (\mathrm{id}_{\mathcal{L}} \otimes \kappa(g))f \bmod S^{p-1}\mathcal{M}_{R_0}\,.$$

(Use that $\mathcal{G}_h$ strictly acts on the $\widetilde{\mathcal{G}}_h$-orbit of $f \bmod S^{p-1}\mathcal{M}_{R_0}$.)

Proposition 4.4. — *κ induces a group isomorphism $\kappa_{<p} : \Gamma_{<p} \longrightarrow \mathcal{G}_h$.*

Proof. — Suppose $g_1, g \in \Gamma$. Let $c \in \mathcal{L}_{\mathcal{K}}$ and $A \in \mathrm{Aut}\,\mathcal{L}$ be such that $(\mathrm{id}_{\mathcal{L}} \otimes \kappa(g))f = c \circ (A \otimes \mathrm{id}_{\mathcal{K}_{<p}})f$. Then we have the following congruences modulo $S^{p-1}\mathcal{M}_{R_0}$

$$\begin{aligned}(\mathrm{id}_{\mathcal{L}} \otimes \kappa(g_1 g))f &\equiv (\mathrm{id}_{\mathcal{L}} \otimes g_1 g)f \equiv (\mathrm{id}_{\mathcal{L}} \otimes g_1)(\mathrm{id}_{\mathcal{L}} \otimes g)f \\ &\equiv (\mathrm{id}_{\mathcal{L}} \otimes g_1)(\mathrm{id}_{\mathcal{L}} \otimes \kappa(g))f \equiv (\mathrm{id}_{\mathcal{L}} \otimes g_1)(c \circ (A \otimes \mathrm{id}_{\mathcal{K}_{<p}})f) \\ &\equiv (\mathrm{id}_{\mathcal{L}} \otimes g_1)c \circ (A \otimes g_1)f \equiv (\mathrm{id}_{\mathcal{L}} \otimes \kappa(g_1))c \circ (A \otimes \kappa(g_1))f \\ &\equiv (\mathrm{id}_{\mathcal{L}} \otimes \kappa(g_1))(c \circ (A \otimes \mathrm{id}_{\mathcal{K}_{<p}})f) \equiv (\mathrm{id}_{\mathcal{L}} \otimes \kappa(g_1))(\mathrm{id}_{\mathcal{L}} \otimes \kappa(g))f \\ &\equiv (\mathrm{id}_{\mathcal{L}} \otimes \kappa(g_1)\kappa(g))f\end{aligned}$$

and, therefore, $\kappa(g_1 g) = \kappa(g_1)\kappa(g)$ (use that $\mathcal{G}_h$ acts strictly on the orbit of f).

Therefore, κ factors through the natural projection $\Gamma \to \Gamma_{<p}$ and defines the group homomorphism $\kappa_{<p} : \Gamma_{<p} \to \mathcal{G}_h$.

Recall that we have the field-of-norms identification $\widetilde{\Gamma} = \mathcal{G}$ and, therefore, $\kappa_{<p}$ identifies the groups $\kappa(\widetilde{\Gamma})$ and $G(\mathcal{L}/\mathcal{L}(p)) \subset \mathcal{G}_h$. Besides, κ induces a group isomorphism of $\langle \tau_0 \rangle^{\mathbb{Z}/p^M}$ and $\langle h_0 \rangle^{\mathbb{Z}/p^M}$. Now Proposition 4.1 implies that $\kappa_{<p}$ is isomorphism. □

Under the isomorphism $\kappa_{<p}$, the subfields $\mathcal{K}[s, M] \subset \mathcal{K}_{<p}$, where $1 \leqslant s < p$ (cf. Subsection 3.5), give rise to the subfields $K[s, M] \subset K_{<p}$ such that $\mathrm{Gal}(K[s, M]/K) = \Gamma/\Gamma^{p^M} C_{s+1}(\Gamma)$. In other words, the extensions $K[s, M]$ appear as the maximal p-extensions of K with the Galois group of period p^M and nilpotent class s.

Using that the identification $\mathcal{G} = \widetilde{\Gamma}$ is compatible with ramification filtrations, cf. Subsection 4.2, we obtain the following result about the maximal upper ramification numbers of the field extensions $K[s, M]/K$, where $M \in \mathbb{N}$ and $1 \leqslant s < p$.

Theorem 4.5. — *If $[K : \mathbb{Q}_p] < \infty$, e_K is the ramification index of K and $\zeta_M \in K$ then for $1 \leqslant s < p$,*

$$v(K[s, M]/K) = e_K \left(M + \frac{s}{p-1} \right) - \frac{1 - \delta_{1s}}{p}\,.$$

Proof. — Note first, that the Herbrand function $\varphi_{\widetilde{K}/K}(x)$ is continuous for all $x \geqslant 0$, $\varphi_{\widetilde{K}/K}(0) = 0$ and its derivative $\varphi'_{\widetilde{K}/K}$ equals 1 if $x \in (0, e^*)$ and equals p^{-m}, if $m \in \mathbb{N}$ and $x \in (e^* p^{m-1}, e^* p^m)$.

From Proposition 3.8 we obtain that

$$v(K[s, M]/K) = \max \left\{ v(K(\pi_M)/K), \varphi_{\widetilde{K}/K}(p^{M-1}(se^* - 1)) \right\}\,.$$

Note that $v(K(\pi_M)/K) = \varphi_{\widetilde{K}/K}(p^{M-1}e^*) = e^* + e_K(M-1)$ and, therefore,

$$v(K[1, M]/K) = v(K(\pi_M)/K) = e_K \left(M + \frac{1}{p-1} \right)\,.$$

If $2 \leqslant s < p$ then $v(K[s, M/K)$ equals

$$\begin{aligned} \varphi_{\widetilde{K}/K}(p^{M-1}(se^* - 1)) &= \varphi_{\widetilde{K}/K}(p^{M-1}e^*) + \frac{p^{M-1}(se^* - 1) - p^{M-1}e^*}{p^M} \\ &= e_K \left(M + \frac{s}{p-1} \right) - \frac{1}{p}\,. \end{aligned}$$

□

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