SOFTWARE FOR AUTOMATIC VOLTAGE REGULATION IMPLEMENTED IN REMOTE TERMINAL UNIT

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ABSTRACT

In common distribution networks (DN), once set parameters of automatic voltage regulator (AVR) are very rarely changed. As a consequence, voltage control law, based on which voltage control process is realized, is often not in compliance with current DN state and topology, i.e., voltage profiles realized in DN are far from optimally possible ones. This problem is successfully overcome by the application of voltage control function integrated into the Distribution Management System. Its results are transferred by SCADA system into the substations remote terminal units. Parameters of Programmable Logic Controllers (PLCs) are being modified on the basis of these results. In accordance with new settings and current measurements, voltage control is carried out automatically. With this new solution, possibilities of having dynamic real-time parameterization of voltage control over the SCADA system are created. Verification of the voltage control based on PLC is performed in DN of the city of Sombor, the branch of the Electric Power Distribution Utility Elektrovojvodina, Novi Sad, Serbia.
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INTRODUCTION

Load tap changing (LTC) transformers (including substation and feeder voltage regulators) are key resources for distribution networks (DNs) voltage regulation (control). Control of its tap changer position can be carried out manually in a substation, remotely from a dispatcher control center (DCC) by SCADA system and automatically in a substation based on the voltage control law by automatic voltage regulator (AVR). Although changes of DN topology and DN load allocation are very frequent, in practice the AVR settings change very rarely. Additional problem is that AVR parameters are usually set manually in a substation. It is obvious that significantly better voltage profiles in DN could be accomplished by frequent changes of these parameters, especially if these changes are made in real-time condition (in accordance with the topology and load changes). This voltage control, based on permanent real-time voltage control changes of parameters, represents the basic topic of this paper. Voltage control parameters are changed based on results of voltage control function which is integrated in Distribution Management System (DMS) as one of its basic real-time functions [1,2,3]. Possibilities of real-time optimal voltage control integrated in DMS Software (DMS VC) are presented in [1]. Within this voltage control procedure, tap changer position is remotely controlled in real-time condition. The optimal real-time moving of the tap changer for a position up/down is permanently calculated by corresponding DMS voltage control function. This type of control provides the best results which can be achieved for the given network. Basic problem of such control appears in the case of loss of communication between DCC and substation, when tap changer remains on the last set position. This problem is solved by the voltage control which is presented in this paper. Due to such deficiency, the substation remote terminal unit (RTU) is provided by the classic AVR functionalities. These functionalities are permanently programmed in real-time condition by PLC software. The setting of PLC is carried out from DCC through SCADA system by sending the parameters which define the LTC voltage control law. In case of loss of communication between DCC and substation, voltage control is realized based on last set parameters. In case of longer interruption, parameters of PLC setting are automatically reset to default values. Such voltage control is hereinafter called *PLC voltage control* (PLC VC). Not only high quality of DN voltage control, but also a high level of reliability of realization of such a solution is achieved by this application. PLC VC is easier for building in and is significantly cheaper than classic voltage control (classic VC) which is carried out based on AVR.

After Introduction, description of PLC VC and its parameters are given. Third part of the paper provides results of PLC VC application in three different periods on the example of DN of the city of Sombor (the branch of the Electric Power Distribution Utility Elektrovojvodina, Novi Sad, Serbia). Also, possibilities of PLC VC operation (based on remotely controlled RTU software) are compared with the operation of classic VC (based on once set AVR) and DMS VC (based on real-time control of tap changer position, which is based on DMS software results). Upon conclusion given in the fourth part, fifth part of this paper provides used references.

PLC VOLTAGE CONTROL

Classic VC and PLC VC are based on the voltage control law [1]. The basic principles of the PLC VC are given in Fig. 1: 1) measured values of the current (I_{MV}) and voltage (V_{MV}) on the LTC transformer secondary side are introduced in RTU (MV – medium voltage); 2) voltage deviation is determined – difference of V_{MV} and set-point voltage value (V_{SP}) which should be measured for I_{MV} on the basis of voltage control law; 3) based on amount of the voltage deviation, if necessary, PLC initiates the change of tap changer position with the aim to annul the voltage deviation.

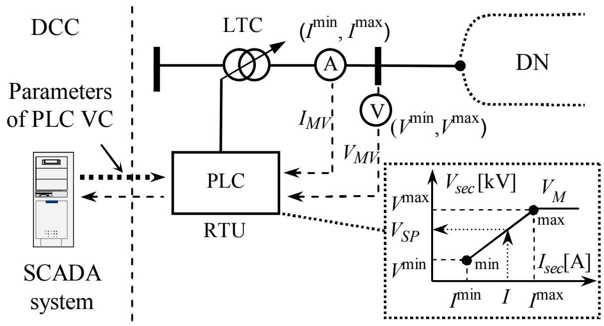


Fig. 1 – PLC VC

Essential difference between PLC VC and classic VC is the fact that voltage control law of the classic VC is usually adjusted only once for the entire considered period (based on information of the states with expected minimum and maximum load and expected DN topology). Unlike this approach, DMS VC [1] and here considered PLC VC are based on results of the resident real-time DMS functions (Topology Analyzer, State Estimation and Near-Term State Forecasting), i.e., on information with sufficient quality level of current DN topology and state [5].

In order to realize PLC VC, it is necessary to define the following parameters in accordance with Fig. 2:

V_{SP} *Set-point voltage* in accordance with voltage control law and current measured on the LTC transformer secondary side;

V_M *Maximum voltage value* on the LTC transformer secondary side (independently from its load);

V_{BW} *Bandwidth* – maximum voltage deviation from V_{SP}, for which PLC VC will not operate (this value defines the quality of voltage control – the less the bandwidth is, the less the voltage deviation from the set-point voltage value there is);

T_B *Basic time profile* is used for the choice of load profile depending on deviation from voltage control law;

k_{Td} *Time factor* – coefficient of the time delay;

T_d *Time delay* – time from excitation until sending a command to change the tap changer position (this parameter prevents the change of position due to voltage short-term changes). It is defined depending on deviation from voltage control law and chosen basic time profile (Table 1).

V_m *Minimum voltage value* – when this voltage is violated PLC VC sends command to reduce the voltage;

V_v *Maximum voltage value* – when this voltage is violated PLC VC sends command to increase the voltage;

V_m' *Upper turn back voltage* – if violated voltage value turns back under this value excitated PLC VC does not act for the set T_d;

V_v' *Lower turn back voltage* – if violated voltage value turns back above this value excitated PLC VC does not act for the set T_d.

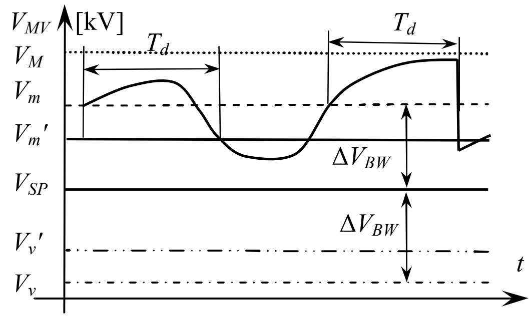


Fig. 2 – Parameters of PLC VC

Control algorithm in RTU is realized by the application of Functional Block Diagram technique, while the blocks themselves are written in Structural Text programming language (specialized language for PLC software programming which is a basic part of the IEC Standard 61313-3 for programming of PLC). The settings of voltage control parameters, which affect the operation of PLC voltage control algorithm, are made by transferring the results of DMS calculation from DCC to PLC, through SCADA system.

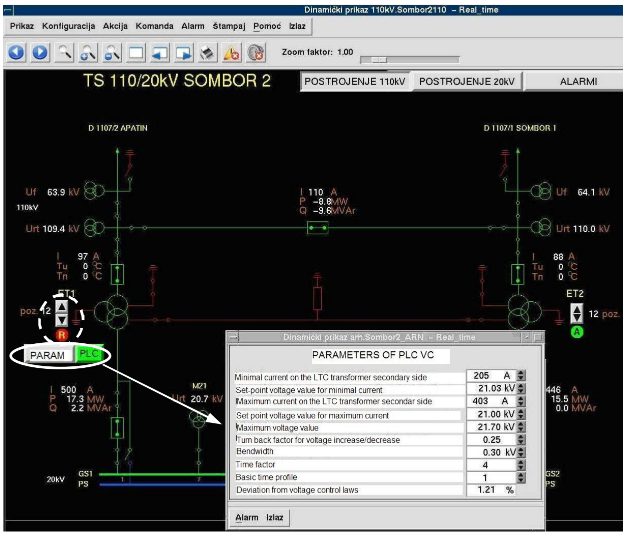


Fig. 3 – Dynamic display of VC in SCADA system

SCADA single-line diagram of a supply substation 110/20 kV/kV with PLC, with specially emphasized voltage control buttons, is shown in Fig. 3. It is possible to choose voltage control type by buttons marked in dotted line: A – classic AVR and R – manual change of position (order given by dispatcher). By choosing of PLC and PARAM button, running of PLC VC and displaying changes of its parameters are enabled, respectively. Used parameters of PLC VC (values of ranges for 20 kV DN are presented in brackets) are presented in the following text:

I^{min} minimal current on the LTC transformer secondary side, (0÷500 A);

V^{min} set-point voltage value for I^{min}, (18÷22 kV);

I^{max} maximum current on the LTC transformer secondary side, (0÷1000 A);
V^{max} set-point voltage value for I^{max}, (18÷23 kV);
V_M maximum voltage value, (21÷23 kV);
k_p turn back factor for voltage increase/decrease, (0÷0,5);
V_{BW} bandwidth, (0÷4 kV);
k_{Td} time factor, (1÷10);
T_B basic time profile, Table 1, (1÷4).

Table 1 presents four types of the basic time profiles T_B depending on deviation from voltage control laws which are implemented in PLC VC. Characteristic of each type of T_B is that the values of the result of multiplying voltage deviation and time delay are constant.

Table 1 – Basic time profile

T_B	Voltage deviation, from voltage control laws (%)									
	1	2	3	4	5	6	7	8	9	10
	sec	sec	sec	sec	sec	sec	sec	sec	sec	sec
1	30,0	14,8	10,0	7,5	6,0	5,0	4,3	3,7	3,3	3,0
2	–	30,0	20,0	15,0	12,0	10,0	8,5	7,5	6,7	6,0
3	–	–	30,0	22,5	18,0	15,0	12,8	11,2	10,0	9,0
4	–	–	–	30,0	24,0	20,0	17,1	15,0	13,3	12,0

Based on provided parameters values from DCC, the following parameters are calculated in RTU by PLC software:

$V_m = V_{SP} + V_{BW}$ minimal voltage value;
$V_v = V_{SP} - V_{BW}$ maximum voltage value;
$V_m' = V_{SP} + k_p V_{BW}$ upper turn back voltage;
$V_v' = V_{SP} - k_p V_{BW}$ lower turn back voltage;
$T_z = f(T_B) \times k_{Tz}$ time delay.

Voltage deviation is determined by comparison between measured value of V_{MV} and expected value of V_{SP} which should be realized based on voltage control law (in accordance with I_{SN}). Based on voltage deviation, if required, change of tap changer position is initiated, with the aim to annul the voltage deviation, Fig. 1. For the application of PLC VC it is only necessary to implement the PLC software in the RTU and in the SCADA system server of DCC. For the purposes of DMS calculations, measured values of voltage and current are transferred to DCC as well by SCADA system.

VERIFICATION OF THE PLC VOLTAGE CONTROL

Experiments with PLC VC are carried out in the period from June to November 2010 in a part of the DN of the city of Sombor, which is supplied with electric energy through LTC transformer 110/20 kV/kV (31,5 MVA) in the supply substation "Sombor 2". Supply substation is supervised and controlled by SCADA system. Its DN, with 137 km of total lengths and 136 distribution substation 20/0,4 kV/kV, supplies with electric energy 12.124 customers in the city of Sombor and a few surrounding settlements.

In the following text, results of experiments for three different periods – period A (from June 3 till June 14); period B (from August 13 till August 23) and period C (from October 22 till November 23), are presented.

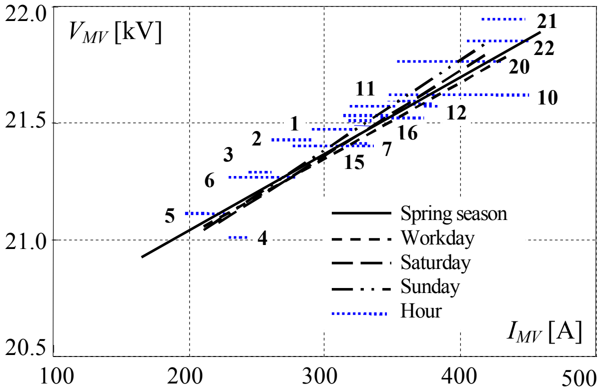


Fig. 4 – Voltage control law (spring season)

During the experiment, parameters of the PLC VC (voltage control law) are adjusted in accordance with the entire season, characteristic workday, Saturday, Sunday and every hour of the considered period. Voltage control law profiles for spring season are given in Fig. 4. Fig. 5 shows the results of PLC VC with workday profile. The following parameters were used in the experiments: V_{BW}=1,25 % (0,25 kV), which is less than one degree of control 1,6%; first basic time profile T_B=1; k_{Td}=4 (for 1% of the voltage deviation T_d=30×4=120 sec. The number of tap changer tripping was 11 per day (Fig. 5 presented by filled black points). Based on shown results, it can be noticed that by the application of PLC VC, voltage on the LTC transformer secondary side is within set limits (bandwidth).

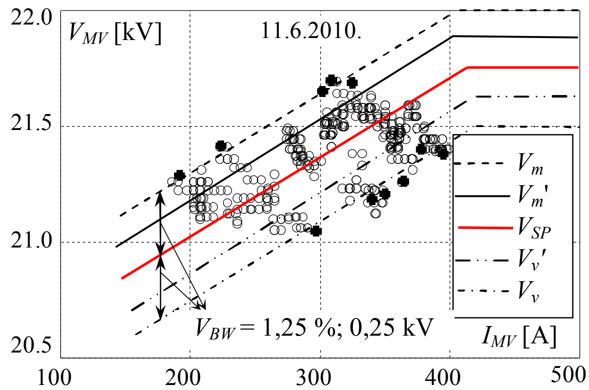


Fig. 5 – Application of PLC VC – values of 20 kV voltage

Results that would be accomplished by the application of DMS VC (permanent real-time control of tap changer position) are shown given in Table 2 (for seven distribution transformers, for period B). They are compared with the results of PLC VC (permanent real-time control of voltage control law). ΔU is the voltage deviation of estimated voltage value from optimal voltage value on LV busbar, and D is the damage that customers suffer due to this deviation [1]. Average voltage deviation values for PLC VC and DMS VC are 2,13 % and 1,94 %, respectively. Consequently, for PLC VC ΔU is increased for negligibly small value, 0,2 %.

Table 2 – Effects of application of PLC VC and DMS VC

Distrib. transform. 20/0,4 [kV/kV]	Rated [kVA]	PLC VC			DMS VC		
		D	ΔU		D	ΔU	
		[m.u.]	[V]	[%]	[m.u.]	[V]	[%]
Apat.-Š.	160	138.674	12,6	3,03	123.963	12,15	2,9
Somb.-Ž.	160	114.921	14,2	3,39	101.515	12,52	3,00
V. Nazor	630	52.861	8,08	1,91	31.588	7,18	1,74
Blok 273	160	89.730	12,7	2,45	83.730	11,38	2,75
Kozara K.	160	139.612	6,78	1,58	124.372	7,26	1,69
Škola	400	189.396	6,5	1,56	177.222	3,97	0,95
Istarska 1	630	184.695	4,1	0,99	151.038	2,21	0,53
Total		681.036			585.736		
Average			9,41	2,13		8,10	1,94

Table 3 gives results of experiments performed during 2008 [1] and 2010 for three types of VC. The row that corresponds to year 2008 proves that DMS VC is significantly more efficient than Classic VC in the following proportion of voltage deviations: 7,73/13,24 or 1,89/3,24. The row that corresponds to year 2010 proves that PLC VC is very close to DMS VC (the best voltage control) in the following proportion of voltage deviations: 8,10/9,41 or 1,94/2,13. It can be noticed that the results obtained by the application of DMS VC and PLC VC are significantly better than the results obtained by the application of classic VC.

Table 3 – Comparison of the effects of the type of VC

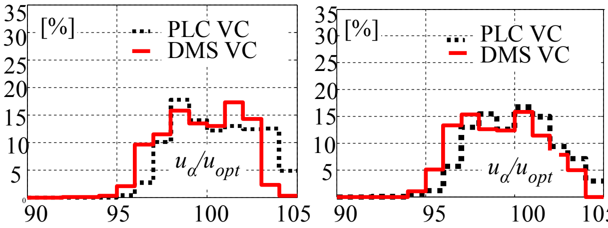
Year	VC type	ΔU		VC type	ΔU	
		[V]	[%]		[V]	[%]
2008	Classic VC	13,24	3,24	DMS VC	7,73	1,89
2010	PLC VC	9,41	2,13	DMS VC	8,10	1,94

Table 4 shows the ratios of expected and optimal voltage values on LV busbars of distribution transformers – u_α/u_{opt}, $\alpha\in\{PLC, DMS\}$, where PLC and DMS refer PLC VC and DMS VC, respectively. These ratios are quantified by expected ($\bar{x}$), minimal (min) and maximal (max) values and values of standard deviation (σ).

Table 4 – Voltage quality of LV buses

period	VC type	u_α/u_{opt}				ΔU			D [10^3 m.u.]
		$\bar{x}$	min	max	σ	1%	2%	5%	
A	PLC	0,99	0,91	1,04	0,95	39.48	79,50	99,98	10.893
	DMS	0,99	0,93	1,03	0,75	42,24	62,58	99,93	10.507
B	PLC	1,00	0,94	1,07	0,88	26,25	56,97	99,98	8.669
	DMS	0,99	0,93	1,05	0,80	26,46	59,54	99,51	8.038
C	PLC	1,00	0,92	1,05	1,17	29,35	59,77	99,41	18.614
	DMS	0,99	0,94	1,04	0,94	28,27	52,36	98,97	15.848

In accordance with all three criteria, it is obvious that PLC VC is practically as efficient as DMS VC. But PLC VC approach completely maintains reliability of its realization. Efficiency of PLC VC in relation to DMS VC is considered for period B and C. Deviation of voltage values of LV busbars of 136 distribution transformers is shown in Figures 6a and b. It can be noticed that the values of voltage deviation obtained by the application of PLC VC and DMS VC are approximately the same.



a) summer *b) autumn*

Fig. 6 – Diagram of the percentage share u_α/u_{opt}

4. CONCLUSION

This paper presents distribution network voltage control on the basis of PLC. Not only qualitative voltage control of a DN is achieved but also a high degree of reliability of PLC application realization is maintained in case of lack of communication between DCC and substation. For this purpose, RTU software in supply substation 110/x kV/kV is expanded with the function which classic AVRs have. Changes of parameters of voltage control are permanently made remotely from DCC by SCADA system (in accordance with changes of topology and DN state). Efficiency of real-time PLC VC is confirmed by its application in real DN.

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