Investigation of very fast-front transient overvoltages for selection and placement of surge arresters

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***Abstract*—An analysis of very fast front transient overvoltages, generated as a result of induced effects of lightning, across a photovoltaic plant is investigated. The EMTP-RV version 3.3 computer software platform is used to simulate surge voltage magnification. Selection and placement of surge arresters for effective protection of power transformers are conducted. Results show that selected arresters placed on bus 4 and coordinated with those placed on bus 5 and 3 ensure surge amplitude reduction of 33% on bus 4.**

***Index Terms*—Very fast-front transient, voltage magnification, surge arrester, power transformers, empt-rv, backflash.**

I. Introduction

Very fast-front transient (VFFT) overvoltages generated due to switching operations or lightning strikes consist of major causes of insulation ageing and/or failure in power systems and equipment thereof [1]-[3]. One of such power system equipment may consist of power transformers, which can experience dielectric and windings failure as a result of induced resonant phenomena caused by VFFTs [4, 5]. Insulation ageing or dielectric breakdown usually translates into either phase to ground or phase to phase faults in power networks [6]-[8]. Surge voltage and/or current amplitude magnification, followed by back flashes at several junctions of power networks, present enormous challenges to commonly known protection or mitigation techniques [9, 10]. Surge arresters are generally used for mitigation or suppression of all types of transient (switching or lightning) that may be induced in power systems. However, in the context of possible challenges related to succesfull operation of surge arresters, correct selection and placement followed by proper coordination of these devices are critical considerations for power system transient overvoltage protection.

For the purpose of this study, a medium voltage (MV) size photovoltaic (PV) solar plant feeding into a high voltage (HV) transmission grid is used. The amplitude of VFFT overvoltages generated by lightning impulses are simulated using the Electro-Magnetic Transient Program - restructured version (EMTP-RV) 3.3 software package. In addition, an analysis of arrester selection, placement and coordination technique is attempted in order to achieve acceptable protection margin against transient or surge voltage rises across MV transformers of the PV plant. To this effect, the selected and coordinated arresters placed in different bus locations 4, 5 and 3 have proven to have curbed surge voltages generated at bus 4 by 33 % which falls within the permissible protection level of the system.

II. PV Plant Simulation

A. Plant Description

The PV plant under investigation consisted of two major sections: the DC and AC MV sides. The DC side was made up of four PV arrays, each consisting of 2500 modules connected in series-parallel configurations. Each PV array was designed to feed a voltage of 1 kV DC to a pulse-width modulator (PWM)-based DC/AC converter for an ouput voltage of 0.3 kV AC. The AC side of the PV plant consisted of 4 $\times$ 750 kVA, 0.3/22 kV power transformers fed from the inverter outputs, and 3 $\times$ 300 mm^2 and 0.24 km long cross-linked polyethylene (XLPE) insulated power cables that connect the plant tho the HV transmission grid through a 22/132 kV power transformer. The source of transient overvoltage such as considered in this study is VCBs located on the HV side of the power transformers of the MV plant. The plant under investigation is shown in figure 1.

B. Parameters of the PV Plant

The parameters used in the PV plant components are indicated in Table I.

TABLE I: Plant Parameters

Plant Component	Parameters
PV array	C = 1 nF
PWM inverters	1.4 MW
MV transformers	YgD, $X = 6\%$
XLPE Cables	R = 0.1 Ω/km, X = 0.094 Ω/km, C = 0.367 μF
HV transformer	YgD, $X = 11\%$
Grid	650 kW, 800 kVAr

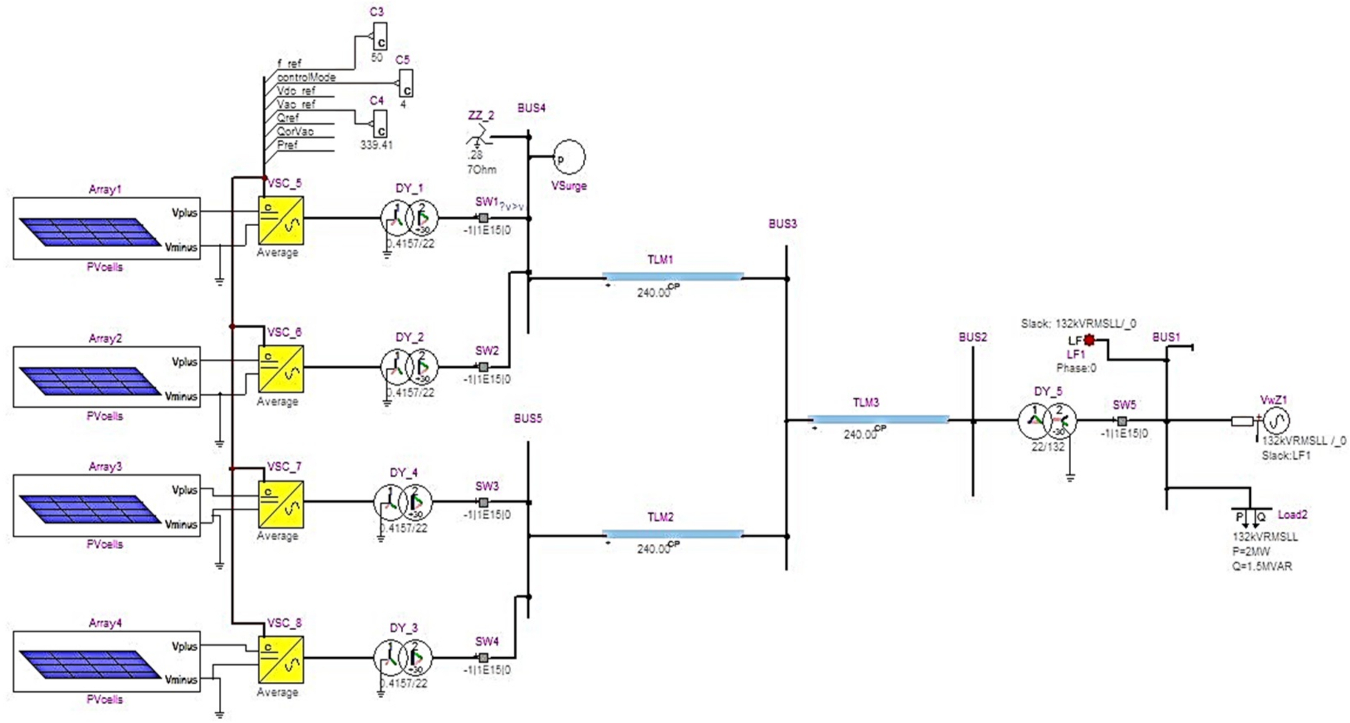

Fig. 1: PV Plant under investigation

C. Surge Voltage Generation

Transient overvoltage such as considered in this investigation is originated from lightning impulses. This operation is therefore simulated in the EMTP-RV platform using 1.2/50 μs voltage surge waveform which is produced by connecting a transient source to bus 4. The surge voltage induced conforms to the IEC standards of VFFT overvoltages [11, 12]. The mathematical model of the surge voltage applied for this simulation is given as follows:

$$v\left(t\right) = V_m\left[e^{\alpha t} - e^{\beta t}\right] \tag{1}$$

where

$v(t)$: instantaneous value of the surge voltage, and
V_m : amplitude of surge voltage, and
α : rise time coefficient (α<0) , and
β : decay time coefficient (β<0), and
t : time.

For the purpose of this study, the amplitude of the worst-case scenario of the surge voltage (VFFT) is used. A peak value of 100 kV, which corresponds to about 4.5 p.u value of the system voltage, is therefore applied in the EMTP-RV simulation runs. Upon the application of this voltage surge on bus 4, higher amplitude transient have been induced in the MV system. These events are shown in figures 2, 3, 4, 5 and 6. Although no transient overvoltage seemed to have penetrated the high voltage grid nor the DC section of the plant, the need for correct selection, optimum placement as well as coordination of surge arresters is still justified in the context of ensuring protection for the MV section of the plant.

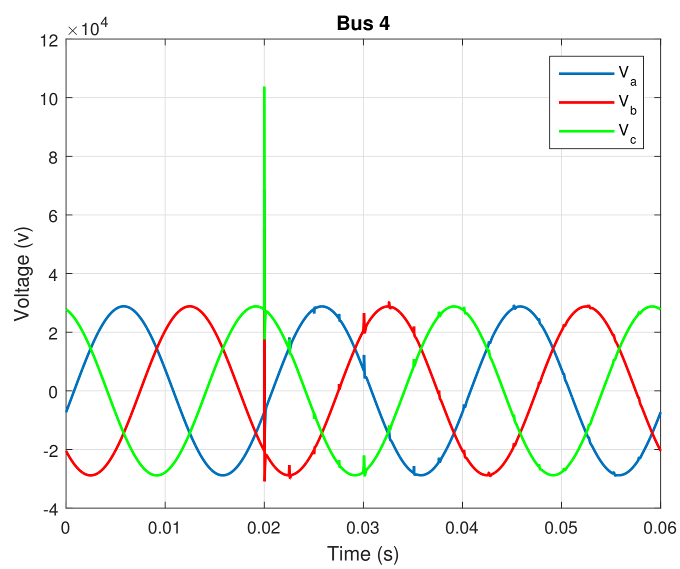

Fig. 2: Voltage surge induced at Bus 4 (no arrester connected)

III. Arrester Selection, Placement and Coordination

Typical selection of gapless arrester for a particular application essentially refers to the determination of the maximum continuous operating voltage (MCOV) or continuous operating

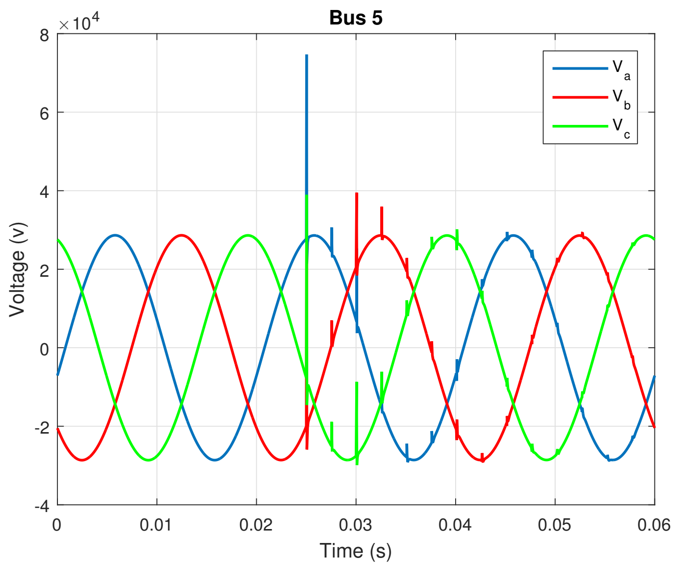

Fig. 3: Voltage surge at Bus 5 (no arrester connected)

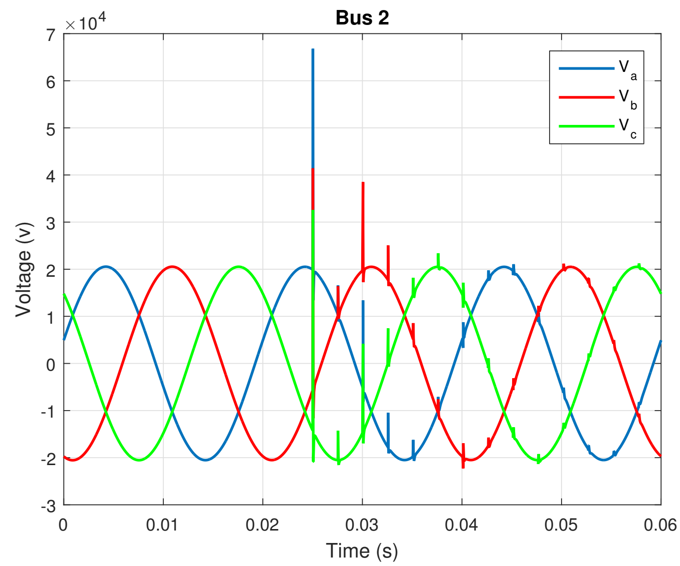

Fig. 5: Voltage surge induced at Bus 2 (no arrester connected)

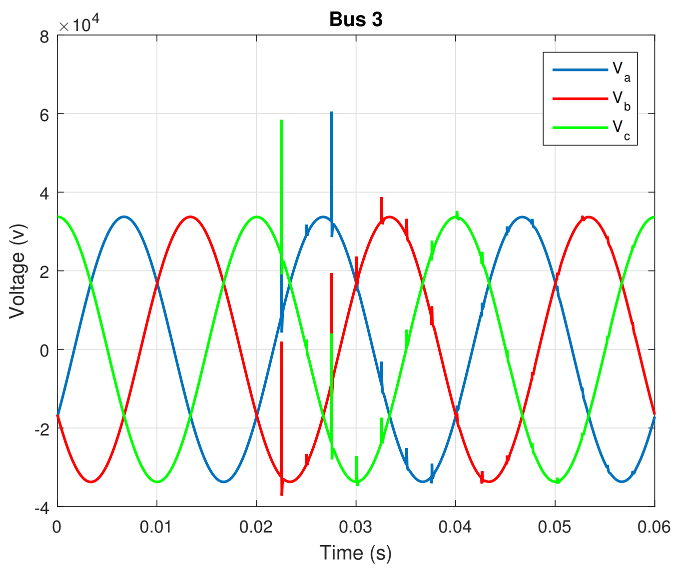

Fig. 4: Voltage surge induced at Bus 3 (no arrester connected)

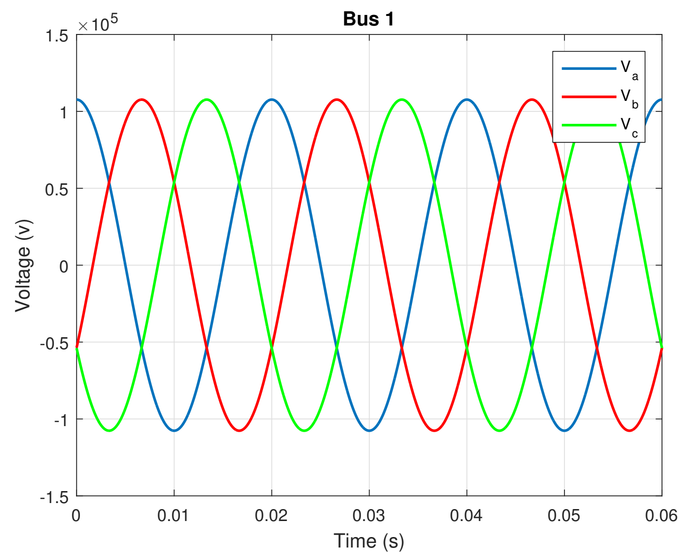

Fig. 6: Voltage at Bus 1 (no arrester connected)

voltage U_C, and the residual voltage of the arrester U_{res} or the clamping voltage [13, 14]. This sizing process of gapless arrester devices requires prior knowledge of the system voltage, the system configurations as well as of potential system overvoltage disturbances. Therefore, a range of U_C values is usually proposed for a given set of conditions (system voltage and configuration). The steps towards the determination of protection margin (how well protection is offered by an arrester) is governed by the IEC margin of protection for commonly encountered transient overvoltages [15]. Therefore for transformer protection, this guide prescribes that the insulation curve should be higher than 115% of the residual voltage curve of the arrester. This in fact indicates that the basic impulse insulation level of the protected equipment (the protection margin) must be 1.15 greater than the residual voltage for effective protection margin to be achieved. Therefore, the following condition should be applied:

$$P_R = \frac{BIL}{U_{res}} \tag{2}$$

where

P_R : protection margin
BIL : basic impulse insulation level of the equipment
U_{res} : arrester's residual voltage.

In order to clamp surge voltage magnifications resulting from backflashes or reflected surges from insulators or junctions, placement distance and coordination of arresters could be very useful to curb or mitigate these challenges. The

IEEE C62.22 [16] prescribe recommendations relative to the maximum permissible placement distance of arresters. This could be obtained using the following equation:

$$D_T = \left(\frac{0.385 \times C \times V_{Bg}}{S} \times \frac{0.957BIL - V_{Bg}}{2.92V_{Bg} - 0.957BIL} \right) \quad (3)$$

where

D_T : maximum distance, and
C : speed of the surge on line, and
V_{Bg} : bus to ground voltage, and
S : steepness of the incoming surge.

The steepness of the incoming surge is estimated using the following equation:

$$S = \frac{K_c}{d_m} \quad (4)$$

where

S : steepness, and
K_c : corona constant, and
d_m : distance from line flashover location to the station entrance.

The flow diagram of the selection and placement process is indicated in figure 7.

IV. Results and Discussion

Simulation results observed across the MV plant before selecting arresters indicate higher peak amplitudes of 103.4 kV (4.7 p.u) on bus 4, 74.7 kV (3.4 p.u) on bus 5, 60.3 kV (2.7 p.u) on bus 3 and 66.8 kV (3.03 p.u) on bus 2. Based on the surge incident point (bus 4), these peak voltages confirm transient overvoltage magnification across the MV plant and pose a threat to the life of power transformers. Therefore, based on the suggested U_C values in the IEC systems [12], the proposed range of U_C applicable to the highest peak amplitude magnification obtained is: 16.8 kV − 24 kV. Considering potential power frequency overvoltages that may be sustained by the system in cases of faults and permissible voltage fluctuations, which could on the long run threaten the life of arresters. The arrester with U_C value of 24 kV is therefore selected for this application. Since the protection focus is directed to the plant transformers (bus 4 and 5) with 1.15 protection margin, and given the surge propagation through the XLPE cables, arrester placement and coordination between busses 4, 5 and 3 should be the most probable mitigation procedure. The results obtained are indicated in table II. It could be observed that three similar arresters connected to bus 4 and further coordinated with single arrester on bus 5 and 3 will provide the greatest deal of transient overvoltage amplitude reduction (33 %). The peak transient voltages measured in these cases are shown in figures 8, 9 and 10. It could also be noted that coordination of surge arresters seems to have caused distortion in the clamping voltage of these devices.

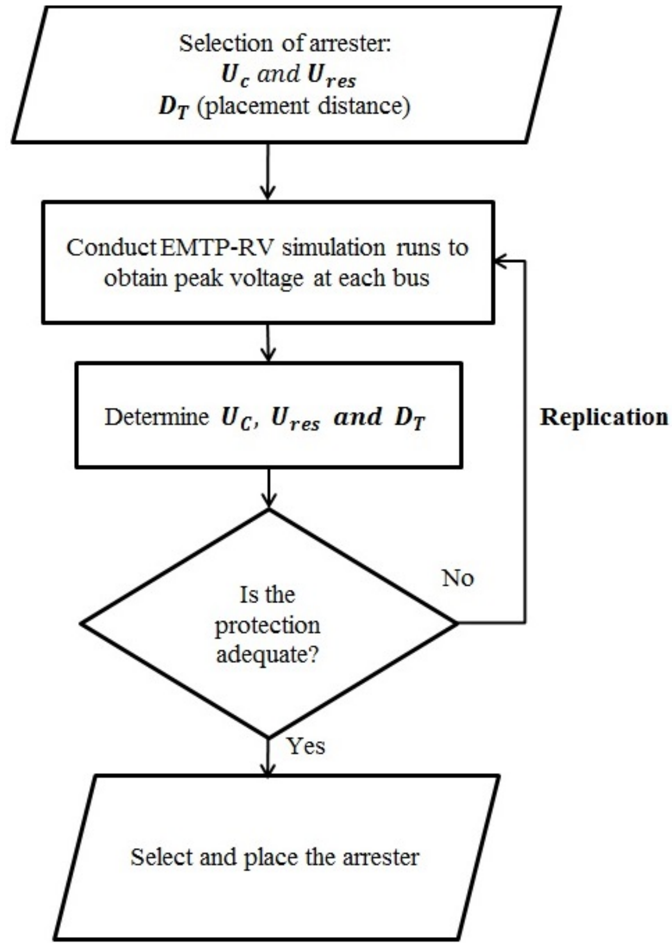

Fig. 7: Flow diagram

TABLE II: Results for arrester selection and placement

Bus	arresters	V_m [kV]	U_{res} [kV]	D_T
4	0	103.7	-	-
4	1	-	40.8	7.62
4	2	-	36.8	
4	3	-	34.1	
5	0	74.7	-	-
5	0 (1 on bus 4)	52.0	-	
5	0 (2 on bus 4)	49.4	-	
5	0 (3 on bus 4)	48.1	-	
5	1 (3 on bus 4)	-	24.5	7.62
3	0 (1 on bus 4)	44.0	-	
3	0 (2 on bus 4)	42.1	-	
3	0 (3 on bus 4)	41.2	-	
3	1 (3 on bus 4)	-	23.8	7.62

V. Conclusion

Amplitude magnification of steep-front transient overvoltages in power systems requires adequate protection for the

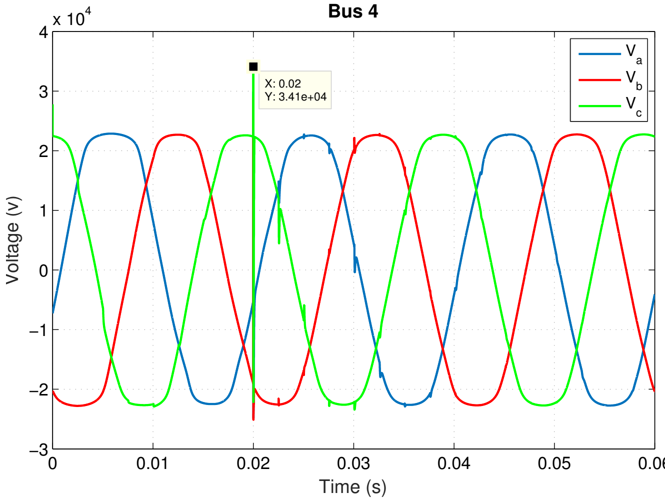

Fig. 8: Residual voltage at bus 4 (3 arresters connected)

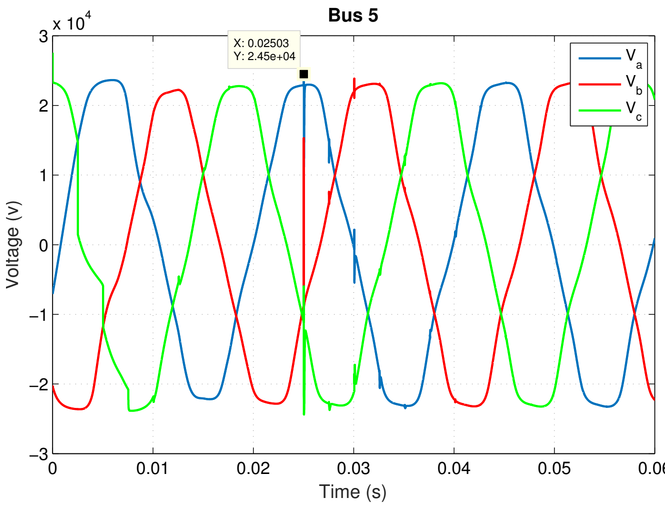

Fig. 9: Residual voltage at bus 5 (3 arresters connected to bus 4 and 1 arrester on bus 5)

safeguard of power transformers and other equipment. Transient analysis of the system should form the backbone for optimum selection and placement of surge arresters. Arrester-based mitigation of voltage surges originated from lightning impulses in the MV section of a PV plant is investigated. This study finds that selection and placement of arresters may not achieve adequate mitigation of surge voltage magnification. Coordination of selected arrester devices may be required post selection and determination of placement distance of arrester devices in order to achieve optimum protection against backflashes in the bus junctions of the MV plant.

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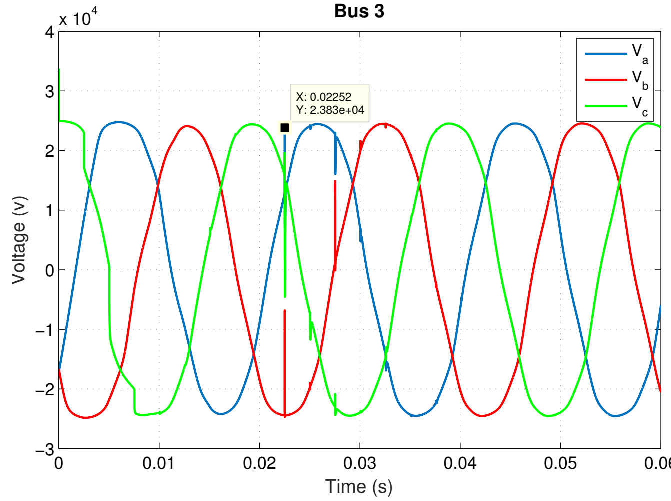

Fig. 10: Residual voltage at bus 3 (3 arresters connected to bus 4, 1 arrester on bus 5 and 1 arrester on bus 3)

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