Vacuum Circuit Breaker induced transients studies for inverter fed step-up transformer

T. Kuczek, M. Florkowski, W. Piasecki

***Abstract*-- This paper addresses transient overvoltages which can occur at a photovoltaic power plant connected to a MV grid by means of a LV/MV transformer. Transient overvoltages can be generated during Vacuum Circuit Breaker (VCB) operations at various scenarios. Those were identified and discussed with consideration of both LV and MV current interrupters. Laboratory measurement of VCB generated overvoltages during transformer energization and de-energization were conducted. An LC filter of a solar inverter was included in the set-up considered and its impact on the transient overvoltage was analysed. Based on measurement results PSCAD models were prepared, which served for further studies. Finally, possibility of high frequency transients mitigation by means of series connected RL chokes was investigated.**

***Keywords*: vacuum circuit breaker, switching transients, mitigation, RL choke, solar converter LC filters, PSCAD**

I. INTRODUCTION

The motivation for this study was driven by significant development and expansion of photovoltaic (PV) power plants in modern electrical power systems. Solar energy is developing fast due to the fact that the investment costs are constantly decreasing, maintenance costs are relatively low and the power production is predictable (the "fuel" is free of charge). It is also reliable, noiseless and quite easy to install. Photovoltaic market has grown by a factor of hundreds of percent during last 13 years [1, 2]. Large PV installations usually require connection to the external grid. The power generated in a PV plant is transferred to the network via power electronic converters and LV/MV transformers. Interconnection to the grid is typically done by a Vacuum Circuit Breaker (VCB), which can be operated at various conditions. There are several known scenarios, where an operation of a VCB may result in generation of significant transient overvoltage. Such operations may be either the scheduled ones (based on power plant operation scheme), or emergency tripping which are often related with breaking of inrush or short circuit currents. This paper points out potentially most hazardous events that can be seen on PV power plant. Laboratory measurement and PSCAD simulations of selected events were studied and discussed.

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II. TYPICAL GRID CONNECTED PV PLANT LAYOUT

The present article covers analysis of possible transient states that can happen on a typical photovoltaic power plant connected to the grid at medium voltage level. PV cells are typically connected in series-parallel strings in order to acquire necessary ratings in terms of output DC voltage and DC current. For the DC to AC conversion power electronic converters are utilized (typically DC/DC and DC/AC in series). The first one (DC/DC) provides control of the voltage at the DC link, which is also responsible for the control of Maximum Power Point of the PV generator. The second converter (DC/AC) – is used for generating a 3-phase AC power output [3, 4]. Most typically 3-phase Multi-Level Voltage Source Inverters are utilized in modern large photovoltaic power plants. At the AC side they are also equipped with LC (or LCL) filters, which decrease the Total Harmonic Distortion (THD) and ripple of the output voltage and current. Their design is performed according to rated current, voltage, switching frequency and maximum level of THD and ripple (exemplary – 5%, according to [5]). At the low voltage side a PV power plant is also equipped with AC and DC circuit breakers, at certain cases with fuses [3]. They are required in order to provide disconnection of the solar panels and inverters during the idle state. Low voltage side is also equipped with surge protection devices, which for the sake of simplicity were not marked in Fig. 1 (they are out of the scope of this study). Transition between LV and MV side is provided by means of a distribution transformer, which is connected to the MV network by means of a MV switchgear and cables. Additionally, authors proposed installation of transient overvoltage mitigation devices referred to as RL chokes. They can be installed directly on MV bushings of the transformer. Their suitability for transients mitigation will be discussed in further chapters. Vacuum circuit breaker utilized for switching operations was marked, too.

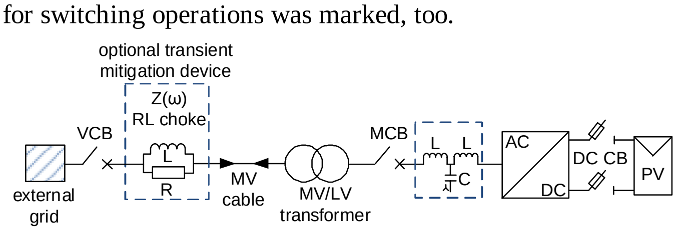

Fig. 1. Layout of interest of grid connected PV plant

III. TRANSIENT STATES IN PV PLANTS ASSOCIATED WITH VACUUM CIRCUIT BREAKERS

Various switching operations are possible in a PV power plants. Some of them are a consequence of the schedule of the plant operation (e.g. disconnection of the transformer from the MV grid at periods of no power production) and some may be the emergency ones. This chapter presents three scenarios distinguished by the authors that may pose a threat to transformer insulation system from the point of view of VCB switching operations. It has to be pointed out that there are multiple available topologies for PV strings, inverters and transformer. The purpose of presented diagrams is to indicate a general concept of a PV operating principles. The sequence of switches operating is marked in each of the diagrams.

A. *PV Plant Start Sequence*

The start sequence of the photovoltaic plant can be always considered as a planned one (Fig. 2). Typical sequence of switching can be described as follows:

1st – DC CB closing, DC link capacitor charging due to PV panels exposed to the sunlight,

2nd – VCB closing, transformer at no-load state,

3rd – MCB closing – reference voltage from network side provided at inverter control,

4th – phase angle and frequency of current or voltage of the fundamental component is recognized by the inverter control – inverter is synchronized "online" with network, power flow can be controlled by appropriate adjustment of inverter's output voltage phase angle and magnitude [6].

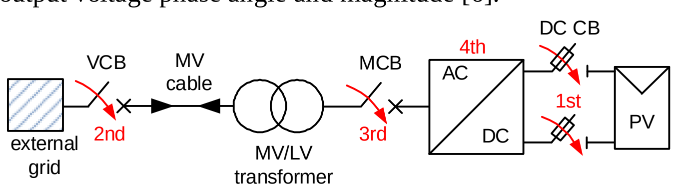

Fig. 2. PV plant start sequence

B. *PV Plant Unsuccessful Start Sequence – VCB Trip on Inrush Current*

The unsuccessful transformer energization is often related to the flow of the inrush current shortly after contacts closing. It may happen that due to protection devices wrong coordination, the transformer will be switched off several tens of miliseconds after energization. Thus, the sequence will look as follows (according to Fig. 3):

1st – DC CB closing, DC link capacitor charging due to PV panels exposed to the sunlight,

2nd – VCB closing, transformer not loaded,

3rd – VCB opening, breaking of inrush current.

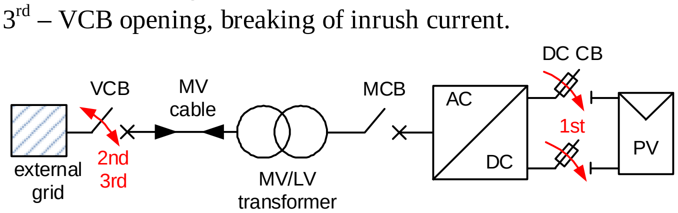

Fig. 3. PV plant unsuccessful start sequence – transformer de-energization under inrush current flow

Such scenario results in very unfavourable switching conditions. It is due to the fact that several Amps of current can be chopped. This increases the possibility of multiple arc re-ignitions and overvoltage escalation.

C. *PV Plant Scheduled Shut Down Sequence*

The sequence of PV plant shut down is not often discussed in the literature. Breaking of high currents should be avoided (due to possibility of several Amps chopping), thus at first, the inverter is blocked. This results in no load state of the LV/MV transformer, thus VCB can be opened with decreased hazard of significant overvoltage escalation. Finally, it is essential to switch off the DC breaker in order to provide disconnection of PV panels from the inverter. Thus, the sequence can be described with the following steps (Fig. 4):

1st – Inverter shut down, blocking signals,

2nd – AC CB (MCB) opening, transformer at no-load state,

3rd – VCB opening, transformer de-energized,

4th – DC switch opening under no-load condition.

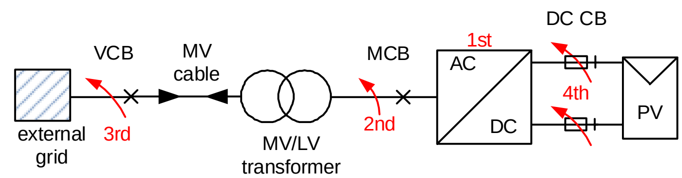

Fig. 4. PV plant scheduled shut down sequence

D. *Transformer de-energization under short-circuit condition*

Short circuits are always a concern for any type of the installation, mainly from the point of view of overcurrents and thermal withstand of working apparatus. It may happen that at the PV power plant a short circuit will occur, either at LV or at MV side. Fault clearance by means of the medium voltage VCB opening is strictly controlled by operator's grid codes – it means that for the certain amount of time shortly after fault occurrence, distributed energy sources (PV, wind) are required to inject capacitive current in order to rise the voltage at the Point of Common Coupling (PCC) [7, 8]. However, after period of time specified by the operator, the VCB can be opened. While clearing of the fault that occurred at the MV side is not problematic from the point of view of overvoltage escalation (mainly resistive current is interrupted), de-energization of transformer short circuited at LV side is of a serious concern. This is due to the fact that a resonance circuit is formed out of cables and transformer capacitances as well as from leakage inductance of the transformer, which is shorted at LV side. This specific case was analysed and is presented in the further section. Thus, the following switching sequence will be observed (Fig. 5):

1st – MCB opening for inverter protection,

2nd – VCB opening, de-energization of shorted transformer.

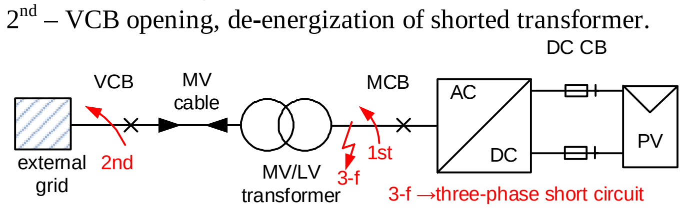

Fig. 5. PV plant scheduled shut down sequence

IV. Vacuum Circuit Breaker and Associated Transient Phenomena Mitigation Methods

A. VCB operation

The principles of VCB operation is well known and broadly described in literature [9, 10]. A VCB uses vacuum as a quenching medium for electrical arc suppression, which appears across the breaker contacts during any switching operation. Since vacuum has very high dielectric withstand (approximately 10 times larger than air at atmospherical pressure) the gap between the fixed and the moving contact can be decreased significantly. In modern constructions it equals to about 10 mm [10].

Transient phenomena during opening operation are associated with the following main effects and features of the VCB, which have the most significant influence on overvoltages generation: chopping of the current before its natural zero crossing, fast rise of the dielectric withstand and ability to break high frequency currents. In modern VCB breaking chambers the current is chopped at several Amps, typically approximately at 3 A_p (peak value). Due to this effect, voltage between the operated contacts starts to oscillate (Transient Recovery Voltage – TRV). Frequency f_n of oscillations is strongly dependent on the equivalent capacitance C_0 and inductance L_0 of the switched off circuit (seen from the operated VCB contacts), according to formula below:

$$f_n = \frac{1}{2\pi\sqrt{L_0 C_0}} \qquad (1)$$

Simultaneously, the dielectric withstand of the gap increases in time generally in a non-linear way. Nevertheless there is a common approach to use a linear approximation providing satisfactory results in most cases:

$$U_R = A(t - t_0)+B \qquad (2)$$

where:

A – Rate of Rise of Dielectric Strength (RRDS),

B – initial dielectric withstand,

t_0 – opening time instant

Each time, when the dielectric withstand exceeds the TRV, the current is chopped again. This process is referred to as multiple arc re-ignitions and it continues until the dielectric withstand of the gap exceeds the crest TRV value. Transient effects during transformer energization are also related to the dielectric withstand, which decreases from its maximum value to zero during contacts closing. Multiple arc pre-strikes can be recorded when contacts are very close to each other. Mainly this effect results in fast charging of the primary winding capacitance.

It has to be added that various circuits can be subjected to switching operations. Most typically those are formed out of MV cables and distribution/arc furnace/motor transformers. However, on photovoltaic power plants LCL filters which are connected at the output of the inverter may also influence transient overvoltages as will be shown further in the paper.

B. VCB transient related mitigation possibilities

In order to mitigate transient overvoltages that may arise during transformer energization or de-energization, several countermeasures have been developed over the years. Most commonly used mitigation devices are surge arresters or RC snubbers. Their impact on the switching process is different, thus at certain applications which require high reliability both of them are combined. Firstly, surge arresters limit the peak value of overvoltage thanks to their nonlinear resistance. However, they do not affect the voltage rate of rise since inductance and capacitance which is added into the circuit is negligible (in comparison to transformer leakage inductance and cables capacitance). In order to limit the TRV, RC snubbers can be utilized. They provide additional capacitance that de-tunes the resonant circuit formed of the transformer inductance and network capacitance [11].

While from the overvoltage mitigation point of view this solution has many benefits, it has some technical and economical limitations. The MV RC snubbers are expensive and require significant amount of additional space in the switchgear. Thus, other solution for dU/dt limitation was proposed, which comprises set of parallel RL filters series-connected at medium voltage side of the transformer. Its suitability for VCB transients mitigation was demonstrated in experiments [12]. The RL choke is characterized by a significant impedance at high frequencies in the range of tens of kHz. It is complemented with phase-to-ground capacitance of the transformer, which forms a low-pass filter. At 50/60 Hz is behaves like a very small impedance (almost transparent) in order to provide minimum voltage drop. It was confirmed by laboratory measurement that it reduces overvoltage steepness (dU/dt), limits overvoltage levels and decreases number of wave reflections. In practice, all of this results in decreased quantity of multiple arc re-ignitions.

V. Analysis of Transient Overvoltages

A. Laboratory experiments

Experimental investigation of all types of transient states described in section III is problematic from the technical point of view. For example, forcing the transformer intentionally into the short circuit state at nominal voltage could result in unexpected failures. Thus, only part of scenarios were studied in the laboratory. However, thanks to that, PSCAD model could be prepared and well fitted according to measurement results, which allowed one to conduct further studies. For the laboratory measurement, scenarios based on PV plant start and shut down were performed. However, in order to reflect the PV plant layout, inverter output LC filters were connected at the transformer LV side, according to Fig. 1. Transformer energization and de-energization scenarios under no-load conditions were performed (VCB closing and opening). The single line diagram of test circuit is illustrated in Fig. 6. Parameters of all components are listed in Table I.

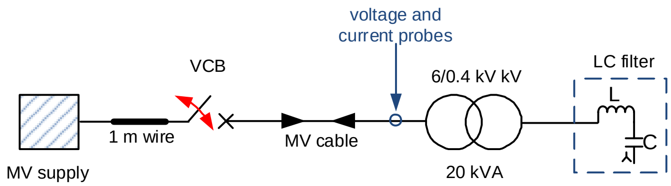

Fig. 6. Laboratory measurement test stand equivalent circuit

TABLE I
COMPONENTS OF LABORATORY TEST STAND

Component	Parameter	Value
MV supply (from 250 kVA transformer)	U_N	6 kV
	I_0	0.25 %
	$u_{k\%}$	4.5 %
20 kVA transformer	U_P/U_S	6 kV / 0.4 kV
	I_0	4.23 %
	$u_{k\%}$	4.3 %
	winding capacitances	C_{p_g} = 3 nF $C_{p\_ph\_ph}$ = 0.2 nF C_{p_s} = 1 nF
VCB	rated voltage	12 kV
	chopping current	3 A_p
1 m wire	inductance	1 μH
MV cable	length	85 m
	impedance Z	50 Ω
inverter output LC filter	inductance L	200 μH
	capacitance C	25 μF

C_{p_g} – capacitance between primary winding and ground
$C_{p\_ph\_ph}$ – capacitance between phases of primary winding
C_{p_s} – capacitance between primary and secondary winding

Voltage was measured for each scenario at the 20 kVA distribution transformer's medium voltage terminals with respect to ground using MV, broad bandwidth probes. Additionally, inrush current was measured in one phase. It was necessary to determine current waveform during energization, since it was used then for magnetization curve fitting in the PSCAD software. Representative waveforms are illustrated in Fig. 7 to Fig. 9. Arc pre-strikes are visible for energization scenario. This is due to multiple voltage breakdowns and fast charging of phase-to-ground capacitance of the primary winding transformer. Moreover, the energy is transferred to the leakage inductance and winding capacitance of the secondary side. Finally, additional oscillations are caused by LC filter capacitance. However, it can be added that transients related to transformer energization are considered as non-critical, since no overvoltage escalation can be seen due to contacts closing.

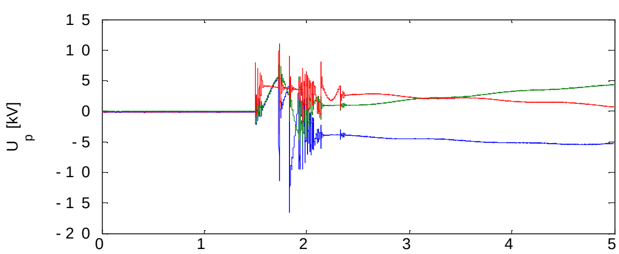

Fig. 7. Laboratory measurement, VCB closing, MV side transformer voltage

A different situation occurs for the VCB opening operation (Fig. 8). Multiple arc re-strikes can be barely seen. This is thanks to the significant capacitance of the LC filter, which decreases natural frequency of the voltage oscillations after de-energization, which results in decreased TRV, too. Finally, Fig. 9 presents recorded inrush current trace that was used for magnetization curve fitting in PSCAD software.

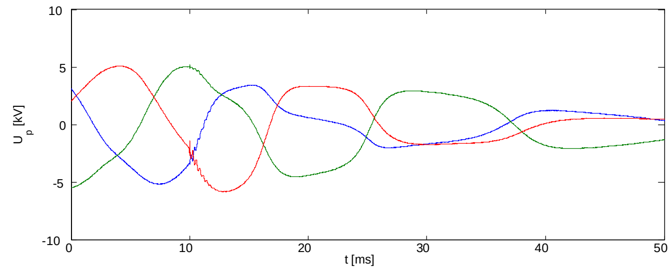

Fig. 8. Laboratory measurement, VCB opening, MV side transformer voltage

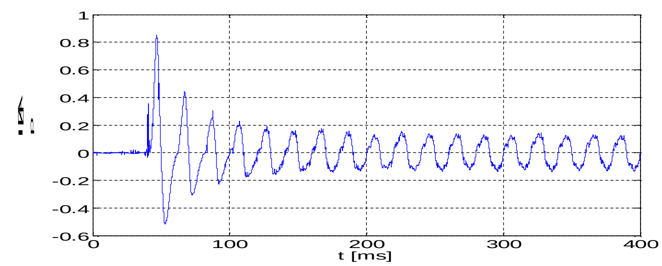

Fig. 9. Laboratory measurement, VCB closing, transformer MV inrush current, phase A

B. *PSCAD simulations*

Based on the measurement results a PSCAD model was prepared, which allowed to perform further studies. Its equivalent circuit is presented in Fig. 10.

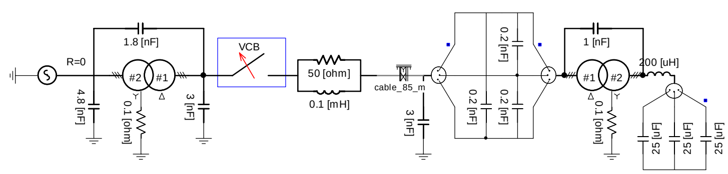

Fig. 10. PSCAD equivalent circuit for laboratory measurement verification

The PSCAD model was prepared according to the data in Table I. The circuit comprised the following components:
1) 20 kVA and 250 kVA transformers: "3-*phase 2-winding transformer*" component complemented with winding capacitances (phase-to-phase and phase-to-ground), core saturation included – knee point voltage at 1.2 pu of U_N [13],
2) MV 85 m cable: surge impedance Z_C = 50 Ω, wave propagation speed v = 200 m/μs and per unit resistance for high frequency (HF) damping effect R_0 = 0.05 mΩ/m,
3) VCB: modelled according to principles from section IV.A and formula (2) by means of CSMF blocks (*Continuous System Model Functions*), A = 4.5 kV/ms (measured value), B = 0 (for worst case conditions).

Several simulations were conducted in order to find best convergence of calculated and measured results. Main influence on simulation results in this particular case was provided by the switching time instant. Most convergent simulation results are presented in figures below. One can compare these figures with those presented *section V.A*.

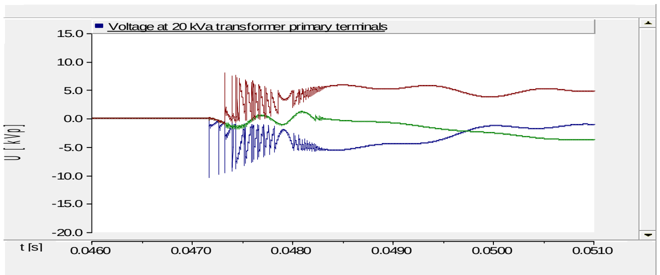

Fig. 11. PSCAD simulation, VCB closing, MV side transformer voltage

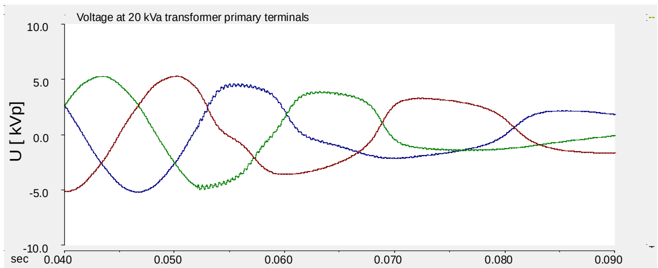

Fig. 12. PSCAD simulation, VCB opening, MV side transformer voltage

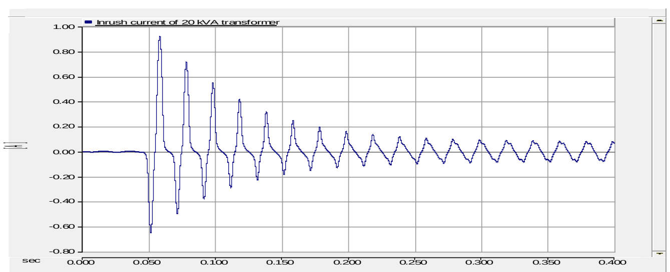

Fig. 13. PSCAD simulation, VCB closing, transformer MV inrush current

Based on results presented above it can be stated that prepared PSCAD model is fitted in satisfactory level, which allows for further analyses of the cases which were not examined experimentally. In this article calculation of overvoltages during breaking of transformer inrush current as well as de-energization of transformer short-circuited at low voltage side are presented. For first scenario, the current that was plotted in Fig. 13 was interrupted by VCB. It can be deduced based on the inrush current waveform that it is more severe condition due to the fact that the current is highly nonlinear and its peak value is higher than during the nominal no-load state. Resulting overvoltages are expected to be more severe than during no-load operating conditions. Additionally, possibility of transients mitigation by means of series connected RL choke was investigated. It was installed before the MV 85 m cable in order to form a low pass filter together with capacitance of this cable. Thus, simulations with and without the RL choke were performed. Calculated waveforms of voltage recorded at the transformer MV terminals are presented in Fig. 14 to Fig. 17. Magnified views were provided in order to show high frequency damping provided by the RL choke. As visible, part of high frequency components were filtered out. Steepness of last arc spark was decreased from 56 kV/µs to 35 kV/µs, so by 38%.

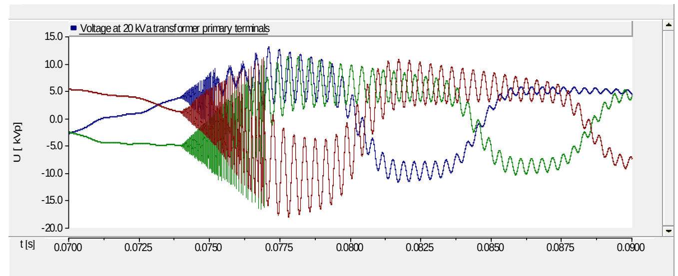

Fig. 14. PSCAD simulation, interruption of transformer inrush current, primary terminals voltage – extended view, RL chokes not connected

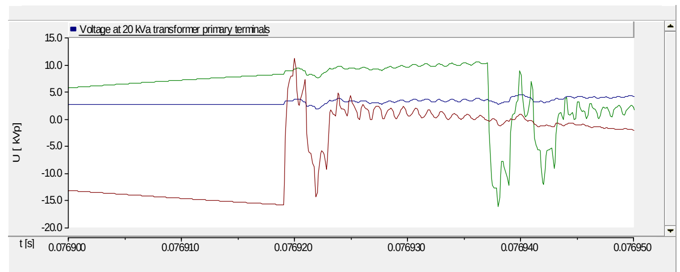

Fig. 15. PSCAD simulation, interruption of transformer inrush current, primary terminals voltage – zoomed view of Fig. 14, RL chokes not connected

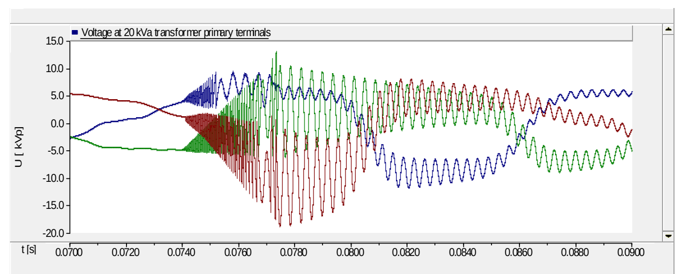

Fig. 16. PSCAD simulation, interruption of transformer inrush current, primary terminals voltage – extended view, RL chokes connected

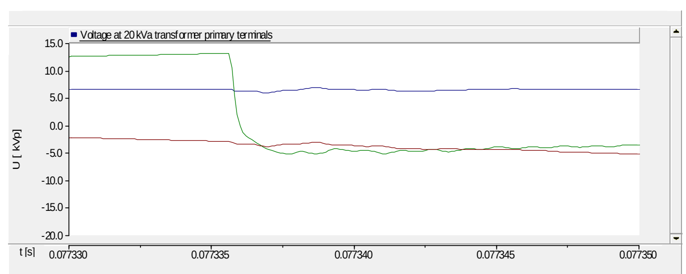

Fig. 17. PSCAD simulation, interruption of transformer inrush current, primary terminals voltage – zoomed view of Fig. 16, RL chokes connected

Second scenario concerned the de-energization of the short-circuited transformer. It was modelled that 3-phase short circuit occurred at the low voltage side. It is a scenario of a practical relevance, since at some applications distances between low voltage busbars are in range of several centimetres, thus it is probable that short-circuiting by small animals can happen. In the model three-phase short-circuit occurs at 0.03 s, the resulting current is interrupted at 0.07 s (arbitrary selected time instant just to show the principle).

Calculated current at MV side is illustrated in Fig. 18. Similarly to the previous case, voltage waveform with and without the RL choke were calculated (Fig. 19 and Fig. 20).

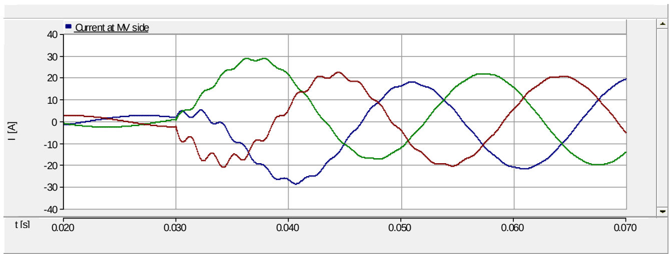

Fig. 18. PSCAD simulation, de-energization of transformer short-circuited at low voltage side, current at MV side

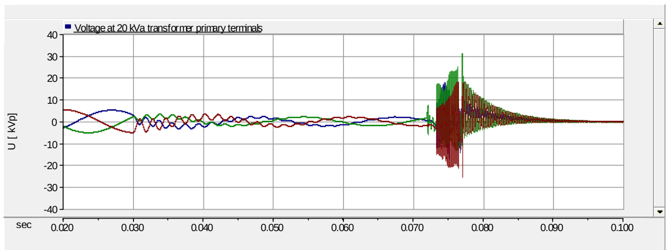

Fig. 19. PSCAD simulation, de-energization of transformer short-circuited at low voltage side, voltage at MV transformer side, RL chokes not connected

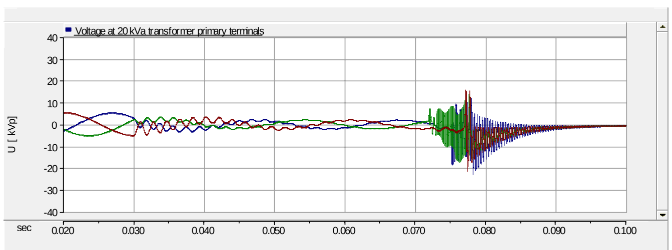

Fig. 20. PSCAD simulation, de-energization of transformer short-circuited at low voltage side, voltage at MV transformer side, RL chokes connected

It can be seen that the current exceeds the nominal current I_N of 20 kVA transformer several times (I_N = 1.92 A). This is a result of the fact that the transformer is three-phase short-circuited at the low voltage side. It means that the current flow is forced by shorted total leakage reactance of the transformer. This current is an inductive one and has magnitude of approx. 20 A_p, which is very unfavourable condition in terms of VCB switching. Since the maximum value of chopping current occurs here (3 A_p), the energy which is trapped in cables and windings capacitances as well as in the leakage reactance of the transformer is significant, which results in a high level and steep overvoltage at the transformer MV terminals (Fig. 20). Application of the RL choke provides significant damping of high frequency components – steepness of the overvoltage was reduced by 47%, (81 kV/µs without the choke and 43 kV/µs with). It can be added that such scenario has low probability of happening, but it should be concerned and identified during the design process of the entire substation. This concerns not only PV applications but all, where short circuit at LV side is possible.

VI. Summary

Research presented in herein paper covers studies of transient states which can occur in photovoltaic power plants. The following most important findings can be pointed out:

1) switching sequences for operation of PV power plants were identified and presented,

2) laboratory measurement of transformer energization and de-energization at no-load state were conducted,

3) based on recorded voltage waveforms, PSCAD model was prepared and fitted in order to accurately reflect the laboratory set-up, developed PSCAD model served for further simulations – analyses of inrush current breaking and interruption of transformer short-circuited at LV side was conducted,

4) it was found that significant overvoltages are possible in two states mentioned above due to the fact that interrupted current is higher than during no-load state, higher chopping current (3 A_p maximum) results in higher energy that causes oscillations of TRV,

5) it was shown that RL chokes installed before the MV cable can decrease the overvoltage steepness, also some high frequency components were filtered out.

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