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VACUUM CIRCUIT BREAKER SWITCHING IN PHOTOVOLTAIC POWER PLANTS – OVERVOLTAGE ANALYSES FOR VARIOUS TOPOLOGIES AND NETWORK CONDITIONS

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Abstract: Nowadays photovoltaic power plants are becoming more and more popular in terms of power generation. Thus, it is necessary to provide safe and reliable working conditions in terms of power generation, conversion and transmission. DC power produced by PV panels is converted by inverter into AC and transformed into medium voltage level by a transformer, where entire power plant can be interconnected with distribution network. Most medium voltage switchgears are equipped with vacuum circuit breakers, which can cause excessive overvoltage escalation during switching off operations. In most severe cases it can lead to damage of working transformers or apparatus. This paper presents modeling techniques for described network in various topologies.

Keywords: pv power plant, vacuum circuit breaker, EMTP-ATP

1. INTRODUCTION

Renewable energy generation is one of the most important topics over the past years. It is commonly reported that photovoltaic power plants will be one of the growing businesses [1]. Thus, it is crucial to provide high performance for working conditions during power generation, conversion and transmission. Last but not least is investigation of transient states related to any switching operations, especially on the medium voltage level.

This paper concerns mainly large photovoltaic power plants (>500 kW), since they are very often equipped with LV/MV transformer and MV switchgear, which allow to interconnect the power plant into the distribution system [2]. Medium voltage switchgears are equipped with various apparatus for measuring, control, protection and switching purposes. This work is addressed to vacuum circuit breaker, which nowadays is the most commonly used switching device in medium voltage switchgears. Thanks to utilized quenching medium (vacuum) it is possible to significantly reduce the size of the interrupter as well as entire switchgear. However, in certain conditions, especially during switching off of the transformers, unfavorable effects may occur [3]. Sometimes, in certain configuration that will be presented further in this paper, switching off operation may lead to voltage escalation which results in effect called multiple arc re-ignitions. It is characterized with high overvoltage peak values and very significant steepness exceeding 200 kV/µs. It was reported in several papers that switching off operations led to failure of working transformers or shunt reactors [4, 5].

This paper will show several network conditions, where switching off operations may lead to negative effects in terms of overvoltages in PV plants. General network layout that was taken under investigation was presented in Figure 1. Moreover, EMTP-ATP modeling techniques are presented with special attention to solar inverter, filters, transformer, medium voltage cables and finally – vacuum circuit breaker.

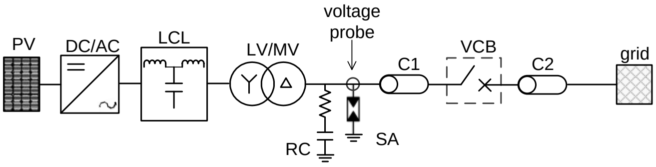

Fig. 1. VCB switching study – overall network diagram; PV – photovoltaic panels, DC/AC – inverter, LCL – inductive and capacitive AC filters, LV/MV – transformer, C1, C2 – MV cables, SA – metal-oxide surge arresters, RC – snubbers

2. OVERVOLTAGE GENERATION DURING VACUUM CIRCUIT BREAKER OPERATING

There are several factors that influence Transient Recovery Voltage (TRV) across the vacuum interrupter's contacts during opening operation: transformer type and ratings, switching conditions (loaded, unloaded, during inrush or short-circuit etc.), presence of medium voltage cables and finally – overvoltage mitigation devices. Attention should be also paid to the transformer's secondary side, since it can energize motors and variable speed drives through power converters. Their inductive/capacitive filters may also influence the final result.

The process of overvoltage generation during current breaking with use of vacuum circuit breaker is presented in Figure 3. It directly refers to diagram presented in Figure 2, which illustrates simplified network diagram consisting of external grid, vacuum interrupter and transformer.

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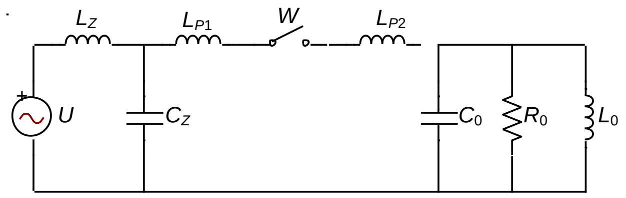

Fig. 2. Equivalent circuit diagram for vacuum circuit breaker switching; L_0, R_0, C_0 – inductance, resistance and capacitance of transformer, *W* – vacuum circuit breaker, L_Z, C_Z – inductance and capacitance of network, L_{P1}, L_{P2} – low impedance connections around VCB

After physical separation of VCB's contacts, current is conducted through the air until it drops to the chopping current value i_{ch} (approximately 2÷5 A for Cu-Cr surface materials). Energy that is trapped in switched off circuit formed from transformer's inductance and capacitance can be calculated according to formula (1). It starts to oscillate with frequency f_0 (formula (2)) and results in maximum overvoltage peak value U_p as described by formula (3).

$$\frac{1}{2}Li_{ch}^2 = \frac{1}{2}CU_p^2 \tag{1}$$

$$f_0 = \frac{1}{2\pi\sqrt{L_0C_0}} \tag{2}$$

$$U_p = \sqrt{\frac{L \cdot i_{ch}^2}{C}} \tag{3}$$

In some configurations and scenarios TRV across the VCB's contacts can exceed the dielectric withstand of the gap causing multiple arc re-ignitions. This process lasts until the TRV will be below the dielectric withstand of the gap [6]. Described phenomenon is a concern in installations when frequent switching operations are expected, like for example arc furnace transformers, PV plants, wind power plants, distribution transformers etc. Several references indicated multiple arc re-ignitions as a cause of transformer's insulation failure, as mentioned earlier. Thus, sometimes as a solution of that problem appropriate overvoltage mitigation devices can be proposed, which can significantly reduce negative effects of transformer's switching operations.

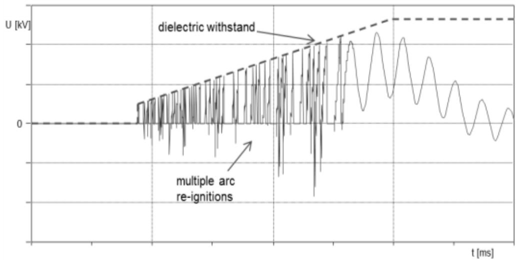

Fig. 3. Voltage between VCB's contacts (solid line) versus dielectric withstand of the gap (dashed line), exemplary waveforms, opening operation

3. EMTP-ATP MODELS DESCRIPTION

This chapter presents detailed description of digital models utilized in the EMTP-ATP circuit that was prepared according to overall diagram illustrated in Figure 1. Power generated by PV panels is converted from DC to AC side by three-phase voltage source inverters, which are commonly used in industrial applications, also on large PV power plants. Topology used for this study was presented in Figure 4. It consists of three legs, one per each phase. Several types of power electronic switches may be utilized in real applications – typically those are IGBTs or MOSFETs. Inverter is equipped with DC link capacitor C_d with capacitance equal to 3400 µF.

The sinusoidal wave is formed with use of method called Phase Width Modulation (PWM) [7]. Its main principle was illustrated in Figure 5. As it is visible, two signals are compared with each other: triangular carrier waveform v_{tri} and modulating waveform $v_{\_ctrl}$. Triangular signal v_{tri} is determined by switching frequency of power electronic switches. In this simulation it was set to 3 kHz (Figure 5 shows 750 Hz for better visibility and easier understanding). Second signal – modulating $v_{\_ctrl}$ has a frequency of desired output waveform, so in this case 50 Hz. Each crossing of carrier signal with modulated signal determines firing pulses for power electronic switches (shifted 120˚ for each phase).

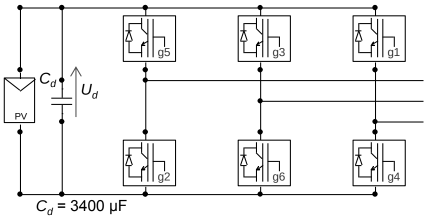

Fig. 4. Three-phase voltage source inverter – equivalent circuit

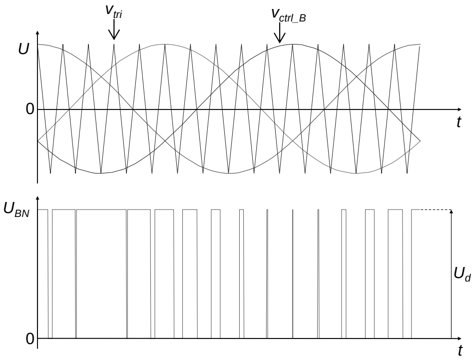

Fig. 5. Three-phase PWM waveforms, main principles

As it is visible in Figure 5, output voltage U_{BN} isn't sinusoidal yet. The high frequency components have to be filtered out. It is achieved by utilization of appropriate inductive-capacitive AC filters. Two commonly used types of filters were presented in Figure 6. Both reduce du/dt and di/dt in the output of the inverter. In this study, filter presented in Figure 6–a was utilized.

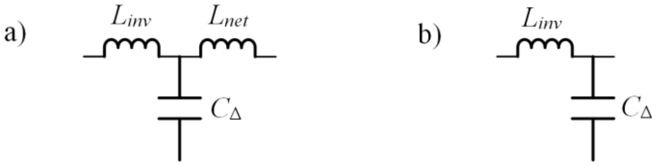

Fig. 6. AC filters, a – LCL type, b – LC type; L_{net} = 88 mH, L_{inv} = 0.15 mH, C_Δ = 200 µF

Once the power is converted from DC to AC it has to be transformed to the medium voltage level through the LV/MV transformer. It was modeled by means of BCTRAN subroutine according to basic data presented in Table 1.

Model was completed with phase-to-phase and phase-to-ground capacitances at the transformer's primary side.

Table 1. LV/MV transformer data

Parameter	value
nominal power, S_N	630 kVA
rated voltage (primary, secondary), U_{NP} , U_{NS}	20/0.315 kV
short circuit voltage, $U_{\%}$	6%
no load current, I_0	1%
load losses, ΔP_{Cu}	6.75 kW
no load losses, ΔP_{Fe}	0.8 kW
primary side capacitance (phase-to-ground)	1.35 nF
primary side capacitance (phase-to-phase)	0.9 nF

Cables that connect medium voltage switchgear with external load (or grid) and with 630 kVA transformer have been represented by means of distributed, lossless line. Surge impedance *Z* of the cable and associated wave propagation speed *v* were calculated according to formulas:

$$Z = \sqrt{\frac{L_0}{C_0}} \tag{4}$$

$$v = \frac{1}{\sqrt{L_0 C_0}} \tag{5}$$

Based on cable's catalogue data, surge impedance and wave propagation speed were calculated 30 Ω and 200 m/µs.

The most important device in the system is vacuum circuit breaker itself, since its behavior will determine transient system response during switching off operation. It is modeled according to method presented in Figure 7.

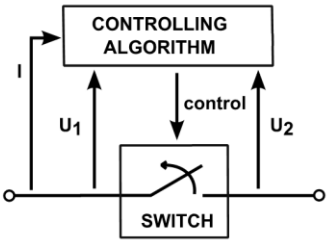

Fig. 7. VCB controlling method, EMTP-ATP implementation

As it is visible, the algorithm (implemented in script language MODELS in EMTP-ATP) compares voltage at the both sides of the vacuum interrupter. Additionally it monitors current that flows in the circuit. During the opening operation, two distinguished phenomena are visible – chopping current effect and dielectric withstand rise between VCB's contacts [8, 9]. In this simulation, chopping current level was set to 3 A. For the worst case conditions it was assumed that current is chopped directly at the time instant when contacts start to separate. Internally implemented dielectric withstand U_R between VCB's contacts starts to rise according to formula:

$$U_R = A(t - t_{open}) + B \tag{6}$$

where:
t – time, s,
t_{open} – opening time (tripping), s,
A – Rate of Rise of Recovery Voltage (RRRV), kV/ms,
B – initial dielectric withstand of the contact gap, kV.

Once this dielectric withstand will be exceeded by the Transient Recovery Voltage (TRV), arc will re-ignite. In certain conditions this process may repeat multiple times until the dielectric withstand will exceed the TRV. It has to be added that the rate of rise of dielectric withstand is strictly dependent on circuit breakers contacts movement speed. In this study, the rate of rise was assumed (20 kV/ms).

The external grid was modeled as a resistive load that forces current to flow. It was assumed that the transformer works under full load conditions, which means that at its primary side current was equal to 18.2 A.

Finally, two different means of overvoltage protection were investigated: surge arresters and RC snubbers (or RC suppressors). Surge arresters were modeled as a nonlinear voltage-current characteristic, based on catalogue data of metal oxide varistors (MOV) for rated voltage equal to 20 kV and energy class 4. RC snubbers were represented as series connected resistor and capacitor connected between transformer primary terminals and ground. Typical values were studied, namely 50 Ω and 200 nF.

4. SIMULATION RESULTS

Singular switching off operations under network conditions specified in previous chapters were performed. The purpose of this study is to present possible overvoltages that can escalate at the transformers primary terminals at unfavorable network conditions. Moreover, methods of overvoltage suppression will be presented. Influence of network topology (cable C1 length – between MV switchgear and transformer) will be discussed, too. Table 2 describes studied scenarios in details.

Table 2. Scope of work (off – not connected, on – connected)

Figure nr	Cable C1 length	surge arrester	RC snubber
8-a	30 m	off	off
8-b	30 m	on	off
8-c	30 m	on	on
8-d	200 m	off	off

It can be noticed, that Figures 8-a and 8-b present scenarios, where multiple arc re-ignitions occur. The steepness (du/dt) of overvoltage is in the range of 220 kV/µs. It is a result of the fact that several amps (18.2 A) are interrupted, which is very unfavorable condition. Moreover, cables that interconnect transformer with MV switchgear ale short (30 m) – it results in insufficient capacitive damping in the circuit. Maximum overvoltage peak values can be reduced be means of surge arresters utilization, but arc re-ignitions cannot be totally eliminated. It is explained with the fact that surge arresters do not provide only negligible additional inductance and capacitance into the system. Figure 8-c represents scenario, where additional means of overvoltage mitigation were installed – RC snubbers. As mentioned earlier, they provide sufficient capacitance to the switched off circuit. Thus, it detunes resonance frequency of the transformer. As a result of that, TRV rises slower (approximately 10 kV/ms) than the dielectric withstand between VCB's contact gap and multiple arc re-ignitions do not occur in this particular scenario. Similar effect can be seen in different topology (200 m cable – Figure 8-d). It is well known that cables provide circuit with their self-capacitance, which acts similar to RC snubbers. In both cases, only insignificant transient oscillations can be noticed, which are not dangerous for transformer's insulation system.

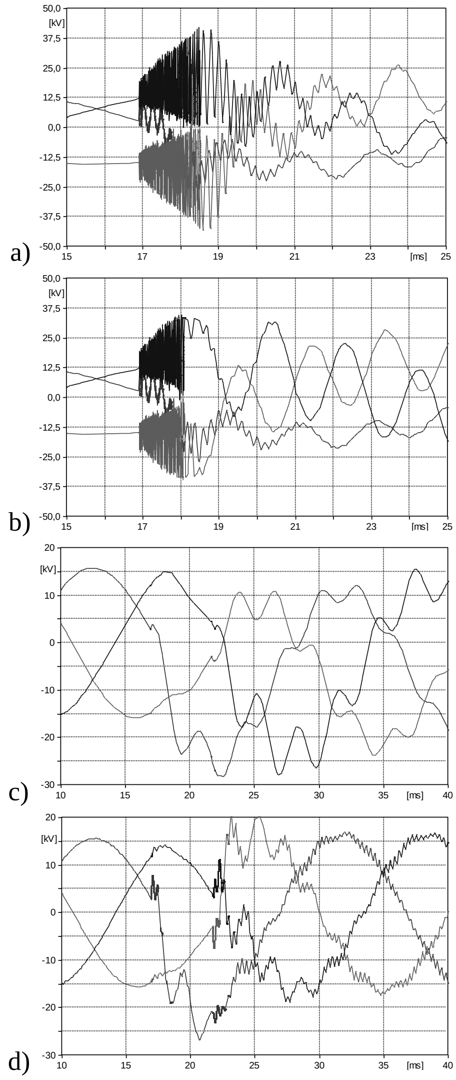

Fig. 8. Voltage at transformer MV side during VCB operation

5. CONCLUSIONS

This paper presented modeling techniques for typical photovoltaic power plants that consisted of PV power source, inverter, AC filters, transformer and medium voltage equipment. Several scenarios of switching off operations were investigated. It was determined that multiple arc re-ignitions are likely to occur in tested system in case of no overvoltage mitigation devices utilized. Partially, negative effects can be reduced by means of surge arresters installation. Higher protection margins are achieved with use of RC snubbers. It was also calculated and discussed that in case of long cables present in the switched off circuit, transient response of the system is less severe.

6. LITERATURE

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OPERACJE ŁĄCZENIOWE WYŁĄCZNIKIEM PRÓŻNIOWYM W SIECIACH ŚREDNIEGO NAPIĘCIA Z UWZGLĘDNIENIEM PANELI FOTOWOLTAICZNYCH PRACUJĄCYCH PO STRONIE NISKIEGO NAPIĘCIA JAKO ŹRÓDŁO ZASILANIA

Słowa kluczowe: elektrownia fotowoltaiczna, wyłącznik próżniowy, EMTP-ATP

Streszczenie: Aktualne tendencje w rozwoju elektroenergetyki wskazują na budowę elektrowni fotowoltaicznych. Zapewnienie odpowiedniego poziomu bezpieczeństwa sieci dystrybucyjnej, poprzez którą będzie wyprowadzona generowana moc ma szczególne znaczenie z punktu widzenia pewności zasilania. Wyprowadzenie mocy z elektrowni fotowoltaicznej odbywa się zazwyczaj poprzez rozdzielnicę średniego napięcia wyposażoną w liczną aparaturę pomiarową, a także łączeniową w postaci wyłącznika próżniowego. Podczas otwierania lub zamykania wyłącznika może dojść do wielokrotnych zapłonów łuku elektrycznego pomiędzy jego zaciskami, co z kolei może prowadzić do uszkodzenia pracujących maszyn i urządzeń elektrycznych. W pracy zaprezentowano przykładowe symulacje przepięć z uwzględnieniem przykładowych topologii sieci.