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VACUUM CIRCUIT BREAKER SWITCHING IN MEDIUM VOLTAGE NETWORKS WITH PHOTOVOLTAIC PANELS AT LOW VOLTAGE SIDE WORKING AS A SUPPLY SOURCE

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Abstract: Breaking of inductive currents with use of vacuum circuit breaker is related to a problem of current chopping before its natural zero crossing. Due to the energy trapped in oscillatory circuit consisting of transformer's inductance and capacitance, the voltage across circuit breaker contacts starts to oscillate. Breaking of dielectric withstand can lead to multiple arc re-ignitions, which can result in generation of waveforms with high steepness and overvoltage peak values. In the present article, the principle of those phenomena was explained. Simulation results of circuit breakers opening operation in medium voltage network consisting of transformer with photovoltaic panels connected at low voltage side was also presented.

Keywords: pv cell, vacuum circuit breaker, overvoltage

1. INTRODUCTION

Solar energy became one of the most important topics in case of renewable energy generation over a past few years. More and more research and development is headed towards grid connected as well as standalone photovoltaic (PV) systems. Moreover, large-scale PV power plants (>500 kW_p) have increasing market share reaching 21.1% in 2011, whereas in 2006 it was 11.3%, as reported in [1].

Typical PV power plant consists of large number of PV cells, which are series-parallel connected in order to obtain desired power along with specified short circuit current and open circuit voltage. Since PV cells produce DC current and voltage for various ambient temperature and irradiance an inverter is needed in order to provide AC sinusoidal voltage as an output. The voltage at LV side is in the range of approximately 300÷1200 V, so a transformer is needed in order to connect the PV plant to the medium voltage (MV) grid [2, 3].

In the MV switchgear that interconnects the transformer with the grid, various apparatus are installed. The most common device that is used for switching operations in medium voltage networks is vacuum circuit breaker (VCB). In this paper a thesis is proposed, that switching operations with involvement of apparatus described above (PV panels, inverters, VCB) can produce high overvoltage peak values, which can lead to transformer failure under specific conditions regarding irradiance and ambient temperature.

2. VCB SWITCHING WITH PV PANELS – GENERAL DESCRIPTION

Problems connected with vacuum circuit breaker switching are well known and widely described in many publications. The principle of VCB switching is presented in details in section 4. In general, occurrence of overvoltages is dependent from a number of factors like transformer ratings, nominal no-load current, number of cables and last but not least – types of loads. In the past main concern were unloaded or lightly loaded transformers (inductively mainly). Nowadays, due to the fact that loads are very often nonlinear (like rectifiers, inverters, variable speed motor drives), overvoltages may also be a threat to the working apparatus and machines since they influence natural frequency of the transformer [4].

In Figure 1 a general approach to the vacuum circuit breaker switching with PV panels was presented. It was assumed, that PV power plant produces power that is converter from DC to AC side through a 3-phase inverter with specific L-C filters (section 4). Furthermore, power is transmitted to the medium voltage grid via 0.315/20 kV transformer. During the steady state operations, for earlier specified conditions regarding weather (irradiance, temperature) switching operations with use of vacuum circuit breaker were performed. Following network was modeled, as presented in Figure 1:

- 125x30 parallel-series connected PV array (281 kW_p) – peak power
- inverter working at LV side of the transformer,
- LV/MV transformer rated at 630 kVA and nominal voltages equal to 0.315/20 kV,
- external network not considered, standalone working conditions, three phase resistive balanced load connected at MV side,
- single core cables, 12/20 kV, 3x120 mm^2,
- surge arresters rated at U_r = 20 kV.

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More details regarding PV array, inverter and vacuum circuit breaker were enclosed in section 4.

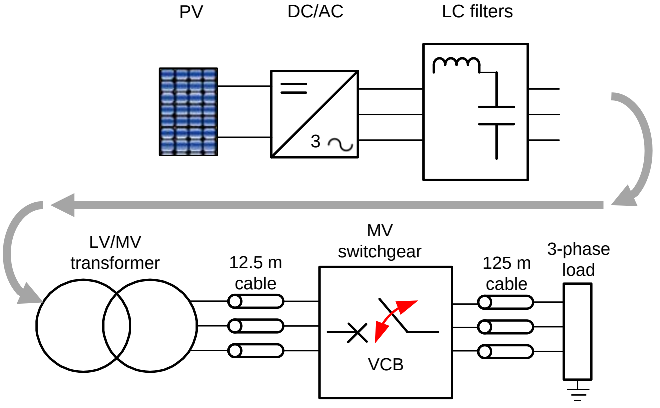

Fig. 1. Vacuum circuit breaker switching with PV panels, general diagram

3. PV CELL – EMTP/ATP MODEL

There are a number of different photovoltaic cell mathematical models, which describe its behavior under various weather conditions. One of the most popular PV cell model is presented in Figure 2 (so called four parameter model). It can be seen that the solar cell is modeled as a current source (I_{ph}) parallel with diode D, which represents reverse saturation current I_0 of PN junction. Moreover, series resistance R_s was utilized in order to reflect internal losses. In this model parallel shunt resistance was neglected, since it was found to have insignificant influence on simulation results, as reported in [5, 6].

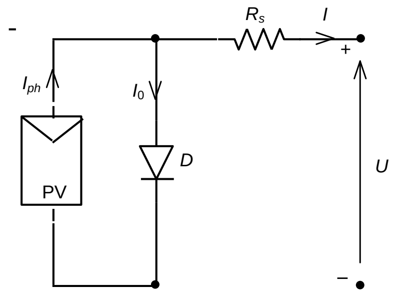

Fig. 2. Photovoltaic cell model – equivalent electrical circuit

The output current I is described with a following equation:

$$I = I_{ph} - I_0\left[\exp\left(q\frac{V+IR_s}{N_sAkT}\right)-1\right] \tag{1}$$

where:

q – charge of an electron, $q = 1.6\cdot10^{-19}$ [C],

T– temperature (˚K),

A – diode ideality factor, [-],

k – Boltzmann's constant, $k = 1.38\cdot10^{-23}$ [J/K],

N_s – number of series connected PV cells in one module, [-].

Total PV generator (array) consists of PV modules arranged in number of parallel (N_{pg}) and series (N_{sg}) connections. Their voltage and current scales proportionally, as presented in equation (2) and (3).

$$I_{total} = I \times N_{pg} \tag{2}$$

$$U_{total} = U \times N_{sg} \tag{3}$$

Each PV cell is characterized by its manufacturer with basic data, typically for Standard Test Conditions (STC), which refer to irradiance and temperature equal to G_{STC} = 1000 W/m^2 and T_{STC} = 25˚C respectively. For this paper, Shell SP75 75 W PV cell was selected (Table 1) [7].

Table 1. Typical PV cell parameters – manufacturer's data

Parameter	value
short circuit current, I_{sc}	4.8 A
open circuit voltage, V_{oc}	21.7 V
maximum power point (MPP), P	74.8 W
current at MPP, I_{mp}	4.4 A
voltage at MPP, V_{mp}	17 A
temperature coefficient of I_{sc}, μ_{Isc}	0.002 A/˚C
temperature coefficient of V_{oc}, μ_{Voc}	-0.076 V/˚C
number of cells in series, N_s	36

In the equation (1) four parameters are unknown: resistance R_s, dark saturation current I_0, photocurrent I_{ph} and diode ideality factor A. These parameters can be evaluated with use of simplified explicit method, proposed in [5] and [6]. Using approximation regarding short circuit current I_{sc}, open circuit voltage V_{oc}, and maximum power point one can form following equations using formula (1):

$$I_{ph} \cong I_{sc} \tag{4}$$

$$0 = I_{sc} - I_0\left[\exp\left(q\frac{V_{oc}}{N_sAkT}-1\right)\right] \tag{5}$$

$$I_{mp} = I_{ph} - I_0\left[\exp\left(q\frac{V_{mp}+I_{mp}R_s}{N_sAkT}\right)-1\right] \tag{6}$$

$$\left.\frac{dP}{dV}\right|_{MPP} = 0 \tag{7}$$

Solving above equations allows evaluating unknown parameters from equation (1), as follows:

$$I_0 = I_{sc}\exp\left(-\frac{V_{oc}q}{N_sAkT}\right) \tag{8}$$

$$R_s = \frac{AkTq^{-1}\ln\left(\frac{I_{sc}-I_{mp}}{I_{sc}}\right)+V_{oc}-V_{mp}}{I_m} \tag{9}$$

$$A = \frac{q(2V_m - V_{oc})}{N_skT\left[\frac{I_{sc}}{I_{sc}-I_m}+\ln\left(1-\frac{I_m}{I_{sc}}\right)\right]} \tag{10}$$

For modeling of PV array in EMTP-ATP a script language MODELS was utilized. Variation of irradiance G and temperature T with respect to the Standard Test Conditions (I_{m_STC}, V_{m_STC}, G_{STC}, T_{STC}) was included, according to formulas (11) and (12), the same scaling is used for I_{sc} and V_{oc}.

$$I_m = I_{m\_STC}\frac{G}{G_{STC}} + \mu_{Isc}(T - T_{STC}) \tag{11}$$

$$V_m = V_{m\_STC} + \frac{N_sAkT}{q}\left(\frac{G}{G_{STC}}\right) + \mu_{Voc}(T - T_{STC}) \tag{12}$$

Current-voltage (*I-V*) curves calculated in EMTP-ATP for variable temperature and irradiance were illustrated in Figure 3. Presented curves are in good match with manufacturer's data [7].

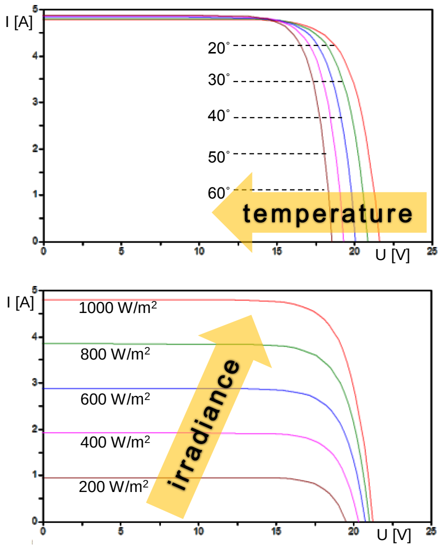

Fig. 3. Current-voltage (*I-V*) curves of PV cell for variable temperature and irradiance calculated in EMTP-ATP

4. AC SIDE COMPONENTS

For power conversion from DC to AC side, a three-phase voltage source inverter was utilized, as shown in Figure 4. DC link capacitor C_d was equal to 3400 µF, whereas values of inductance L and capacitance C in LC filter were equal to 0.15 mH and 200 µF (delta connection) respectively. Phase Width Modulation (PWM) was used for control of power electronic switches, marked with gates signals g1 to g6 [8].

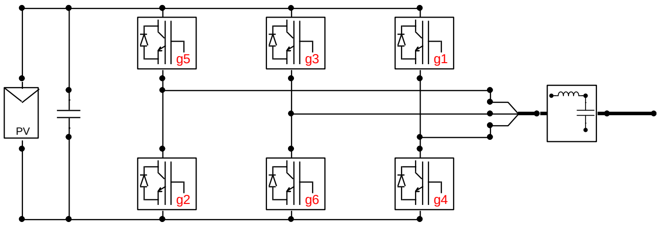

Fig. 4. Three-phase voltage source inverter – equivalent circuit

As mentioned in section 1, vacuum circuit breaker that is installed in MV switchgear is used for switching purposes. Breaking of inductive current is explained in Figure 6 and Figure 7. Figure 6 presents equivalent simplified circuit of network with VCB and transformer primary side.

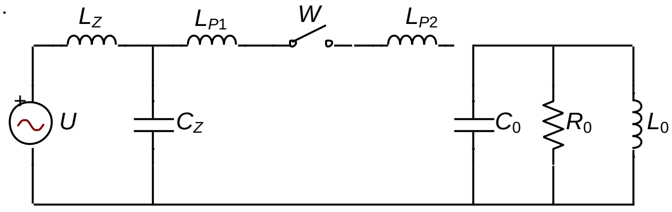

Fig. 6. Equivalent circuit diagram for vacuum circuit breaker switching; L_0, R_0, C_0 – inductance, resistance and capacitance of transformer, W – vacuum circuit breaker, L_Z, C_Z – inductance and capacitance of network, L_{P1}, L_{P2} – low impedance connections around VCB

After physical separation of VCB's contacts, current is conducted through the air until it drops to the chopping current value (approximately 2÷5 A). The energy is being trapped in oscillatory circuit formed from transformer's inductance and capacitance. As a result of it voltage starts to oscillate. When Temporary Recovery Voltage (TRV) across the VCB's contacts exceeds the dielectric withstand of the gap, electric arc re-ignites and current is chopped again. The process is called as multiple arc re-ignitions and continues until the TRV will be below the dielectric withstand of the gap. This phenomenon is very dangerous for working machines and apparatus due to the fact, that depending on transformer's equivalent natural frequency it may produce high overvoltage peak values with steepness exceeding the nominal values. Thus, it may result in speeding of insulation's ageing processes as well as instantaneous failure of the device [9, 10].

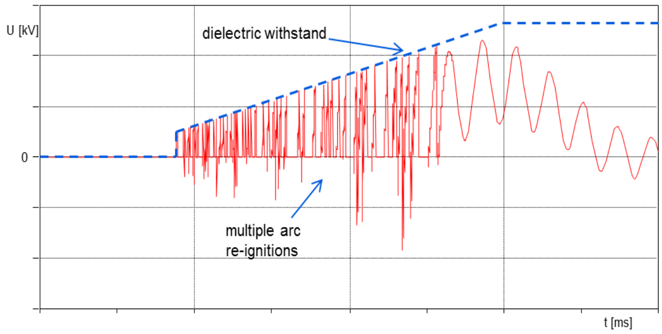

Fig. 7. Voltage between VCB's contacts (solid line) versus dielectric withstand of the gap (dashed line), exemplary waveforms, opening operation

5. TRANSIENT SIMULATIONS – RESULTS

Singular switching operation (opening) of the vacuum circuit breaker marked in Figure 1 was performed. For the PV panels standard test conditions were selected. Current and voltage at MV side of the network during steady state was equal to 17.4 A_p (peak) and 20 kV (RMS, L-L) respectively. Opening operation was issued at time instant of 15 ms with 3A and 1A of first and subsequent chopping current levels. Voltage at transformer MV side was observed for two different network configurations:

1) surge arresters at transformer MV side **not installed**,
2) surge arresters at transformer MV side **installed**.

Recorded waveforms were presented in Figure 8. As it is visible, for both simulation runs multiple arc re-ignitions are well visible. Once the arc is finally extinguished, the voltage follows the sinusoidal source with specific natural frequency oscillations resulting from transformers inductance and capacitance. It has to be said, that this frequency is highly dependent on the load type and value, number and length of interconnecting cables as well as from utilized overvoltage mitigation devices. It this particular one specific network arrangement was studied and presented as exemplary result. Moreover, the effect of surge arresters installation is shown in Figure 8b. It can be noticed, that multiple arc re-ignitions are not eliminated – only maximum overvoltage peak values is decreased. For the decrease of number of arc re-ignitions or its total elimination, utilization of various methods will be investigated with special attention to RC snubbers, which are widely used for switching overvoltages mitigation purposes [11].

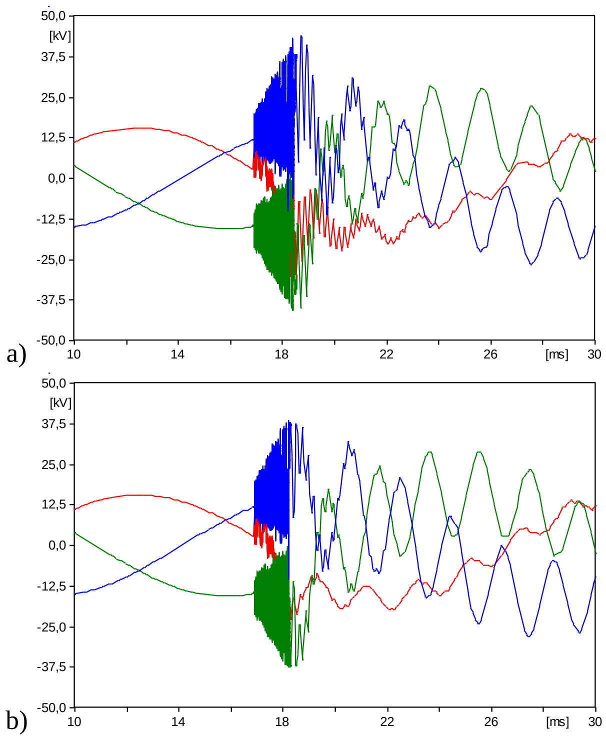

Fig. 8. Voltage at transformer MV side during VCB operation (breaking of 17.4 A_p); a – surge arresters not connected, b – surge arresters connected

6. CONCLUSIONS

In this paper typical PV installation modeling was presented. Explicit method was used for PV cell's parameters calculation. EMTP-ATP software was used for creation of typical PV system consisting of PV panels, inverter, LV/MV transformer and vacuum circuit breaker. It was shown that when load rejection is performed with vacuum circuit breaker it is possible to generate multiple arc re-ignitions as well as high overvoltage peak values.

Further investigation is planned in the future, especially in area of methods of damping presented overvoltages as well as determination if weather conditions (irradiance, temperature) can influence switching behavior of the system.

7. 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: panel fotowoltaiczny, wyłącznik próżniowy, przepięcia

Streszczenie: Wyłączniki próżniowe stosowane w elektroenergetyce średnich napięć charakteryzują się efektem tzw. ucięcia prądu przed jego naturalnym przejściem przez zero. Z powodu energii zmagazynowanej w indukcyjności oraz pojemności transformatora, podczas operacji otwierania napięcie powrotne pomiędzy zaciskami wyłącznika zaczyna oscylować. W momencie przekroczenia wytrzymałości dielektrycznej pomiędzy zaciskami, następuje ponowny zapłon łuku elektrycznego. Zjawisko to może doprowadzić to powstania przepięć o wysokiej stromości oraz wartościach szczytowych. W pracy zaprezentowano wyniki symulacji procesu otwierania wyłącznika próżniowego w sieci z transformatorem zasilanym ze strony niskiego napięcia poprzez panele fotowoltaiczne.