

Short Circuit Current Contribution of a Photovoltaic Power Plant

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Abstract: The grid integration of renewable energies is more and more influencing the short circuit capacity (SCC) of power systems all over the world. The behavior of renewable energy sources, e.g. wind or solar energy, is different from that of classical synchronous generators during symmetrical or unsymmetrical short circuits. The response of renewable energy generation units to short circuits is more or less controllable by the power electronics used in the converter system and the corresponding control algorithms. These differences have to be taken into account during planning grid extensions by the power system operator and designing protective or security functions for the network and its components.

In this paper the authors describe the short circuit current contribution of a photovoltaic power plant. For a 3 MW photovoltaic system equipped with several generation units and connected to a medium voltage power system, three different short circuit scenarios (single-line-to-ground, line-to-line and three-phase faults) and the corresponding short circuit current contribution of the power plant were calculated and the results illustrated and discussed.

Keywords: Photovoltaic, Inverter, Fault Ride Through, Control, Short Circuit Current, Unbalanced Faults

1. INTRODUCTION

The short circuit current in power systems is still dominated by classical synchronous generators of conventional large scale coal or nuclear power plants. As a result of the ever-increasing share of renewable energy sources the short circuit current in the future will differ from the status quo. The fast control of the power electronics in wind and photovoltaic power conversion systems has the capability to control the current injection during balanced as well as unbalanced grid faults.

Large scale photovoltaic (PV) systems are one part of the efforts to increase the share of renewable energy sources in the energy mix. Different configurations are available to feed in power to the grid. In Germany the majority of existing photovoltaic systems are installed in households and are connected to the low voltage level with string or multi string inverters. By contrast large scale PV units are connected to the medium or even to the high voltage network using central inverters. As a consequence large scale PV systems affect the power flow in the interconnected network and so they have to fulfil certain requirements regarding their electrical properties which are usually described in grid codes.

In this paper the authors describe the behavior of a photovoltaic power plant equipped with central inverters during different types of short circuits. The next chapter explains the currently applicable performance requirements for renewable energy sources in Germany regarding the

behavior during short circuits. In the third chapter the control of a three-phase photovoltaic central inverter system is derived in detail. In chapter four the structure of the test power system is illustrated and explained and the fault scenarios are introduced. Chapter 5 shows the EMT simulation results for the three case studies. Hereby the different grid faults (single-line-to-ground fault, two-phase fault and three-phase fault) and the response of the PV power plant are described, and this is followed by some concluding remarks.

2. TECHNICAL REGULATIONS

The past few years saw the publication of grid codes spelling out new requirements for generation units in many countries. The German grid code distinguishes between conventional generation units with directly connected synchronous generators and renewable energy units like wind power, PV or biomass. The regulations contain requirements concerning the active and reactive power control, the power quality, the protective/security functions and the behaviour during grid disturbances. In this chapter the focus is on the requirements regarding the dynamic behaviour during grid disturbances.

The grid code stipulates that generation units should stay connected to the power system during disturbances. Additionally, the reactive current control of the generation unit can be used to support the grid voltage in case of short term voltage drop or increase.

Fig. 1 shows the Fault Ride-Through (FRT) requirements in the German grid code which currently forms the basis for testing. It is required that the unit stays connected to the power system for 150 ms in case of a voltage dip down to 0 p.u. (so called Zero Voltage Ride-Through).

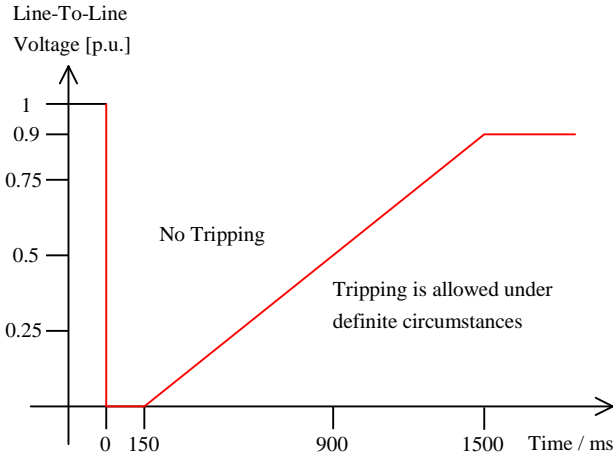


Fig. 1. Fault Ride-Through characteristic

In addition to the FRT capability the German grid code requires the support of grid voltage during fault by the generation units. Fig. 2 describes the required behaviour during voltage drop or increase. In case of overvoltage the unit has to inject inductive reactive current while during voltage drops the unit has to feed in capacitive reactive current. The voltage ΔU is defined as the difference between the pre-fault voltage and the voltage during the fault. The voltage control may include a dead band of ± 0.1 p.u. and has adjustable range for the gain ranging from 0...10 p.u. with a default value of 2 p.u. There are no requirements regarding the positive sequence active current, implying that the active current can differ from zero to its nominal value taking the current limitation of the generation unit into account. The requirements for symmetrical and unsymmetrical faults are related to the positive sequence of the current. Concerning the negative sequence current injection there are no requirements. Hence the negative sequence current is usually suppressed to zero.

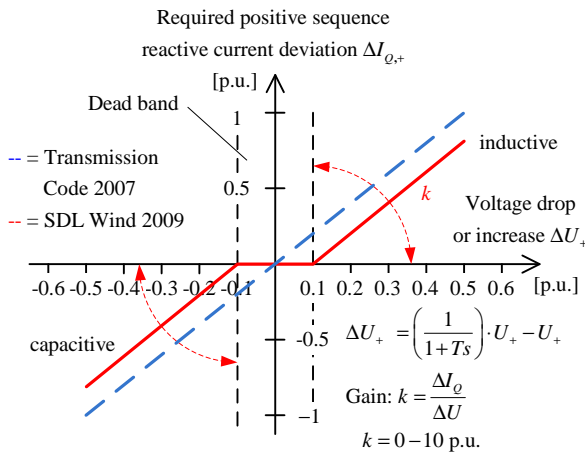


Fig. 2. Dynamic voltage control characteristic

3. CONTROL OF A THREE-PHASE INVERTER

Three-phase PV central inverters usually consist of an IGBT-based two-level inverter. Fig. 3 shows the basic configuration of a two-level inverter system. The inverter and its control are mainly responsible for the electrical behaviour of the unit. Functionalities which need to be performed by the inverter are the Maximum Power Point Tracking and the decoupled control of active and reactive current and thus active and reactive power. In the following subchapter a classical two-dimensional current control aligned to the grid voltage for the positive sequence with an outer (superordinate) DC voltage controller is described. Since there are no requirements for the negative sequence current the target of the control is to suppress the negative sequence current totally.

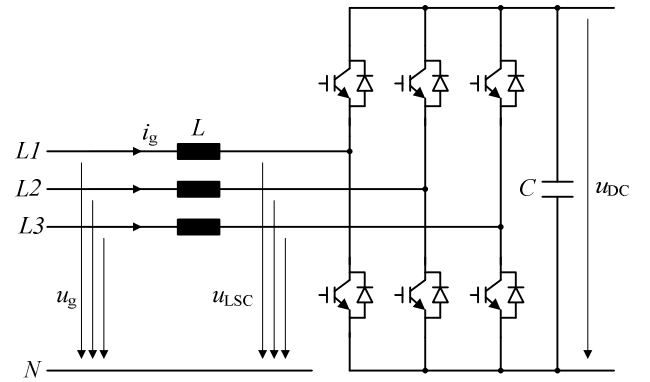


Fig. 3. Principle arrangement of a PV inverter

From the loop equation for the voltages in the circuit described in Fig. 3 the follows equation (1).

$$\begin{pmatrix} u_{g,L,1} \\ u_{g,L,2} \\ u_{g,L,3} \end{pmatrix} = L \cdot \frac{d}{dt} \begin{pmatrix} i_{g,L,1} \\ i_{g,L,2} \\ i_{g,L,3} \end{pmatrix} + \begin{pmatrix} u_{L,SC,L,1} \\ u_{L,SC,L,2} \\ u_{L,SC,L,3} \end{pmatrix} \quad (1)$$

The quantities in any 3-phase system (voltages, currents or flux) can be described by a space vector, consisting of two orthogonal components. Therefore the well-known Clarke transformation converts the abc-components into the alpha, beta-components. In equation (2) the space vector of the positive sequence grid voltage is illustrated exemplarily.

$$\underline{u}_{g,+}^{\angle 0} = u_{g,\alpha,+} + j u_{g,\beta,+} \quad (2)$$

Rewriting equation (1) in complex form, the following equation (3) for the positive sequence with the index + can be derived, where the reference frame is chosen arbitrarily with the notation $\angle 0$ and transformed into the per-unit system.

$$\underline{u}_{g,+}^{\angle 0} = l \cdot \frac{d}{dt} i_{g,+}^{\angle 0} + \underline{u}_{L,SC,+}^{\angle 0} \quad (3)$$

The reference frame of the control system to be described is aligned to the grid voltage. The phase angle of this voltage Θ_g is calculated from the space vector in equation (4).

$$\Theta_g = \arctan \left(\frac{u_{g,\beta,+}}{u_{g,\alpha,+}} \right) \quad (4)$$

The calculated phase angle can be used to transform the space vector in a stationary reference frame into a space vector where the reference frame rotates synchronously with the grid voltage. The transformation is illustrated in equations (5) where the notation $\angle u_g$ describes the reference frame rotating with the phase angle Θ_g .

$$\underline{u}_{g,+}^{\angle u_g} = \underline{u}_{g,d,+}^{\angle u_g} + j\underline{u}_{g,q,+}^{\angle u_g} = (\underline{u}_{g,a,+}^{\angle 0} + j\underline{u}_{g,\beta,+}^{\angle 0}) \cdot e^{-j\Theta_g} \quad (5)$$

In equation (6) and (7) the equation (3) is transformed in a reference frame aligned to the grid voltage. Here the orthogonal components are already separated into the direct and quadrature axis components. ω_0 is the radian frequency of the grid voltage.

$$\underline{u}_{g,d,+}^{\angle u_g} = l \cdot \frac{d\underline{i}_{g,d,+}^{\angle u_g}}{dt} - \omega_0 l \cdot \underline{i}_{g,q,+}^{\angle u_g} + \underline{u}_{LSC,d,+}^{\angle u_g} \quad (6)$$

$$\underline{u}_{g,q,+}^{\angle u_g} = l \cdot \frac{d\underline{i}_{g,q,+}^{\angle u_g}}{dt} + \omega_0 l \cdot \underline{i}_{g,d,+}^{\angle u_g} + \underline{u}_{LSC,q,+}^{\angle u_g} \quad (7)$$

It follows from (6), (7) that the reference voltages of the inverter can be described by the following equations (8) and (9) including the two PI current controllers.

$$\underline{u}_{LSC,d,+}^{\angle u_g} = \underline{u}_{g,d,+}^{\angle u_g} - K_p \left(1 + \frac{1}{T_s} \right) \cdot (\underline{i}_{g,d,ref,+}^{\angle u_g} - \underline{i}_{g,d,+}^{\angle u_g}) + \omega_0 l \cdot \underline{i}_{g,q,+}^{\angle u_g} \quad (8)$$

$$\underline{u}_{LSC,q,+}^{\angle u_g} = \underline{u}_{g,q,+}^{\angle u_g} - K_p \left(1 + \frac{1}{T_s} \right) \cdot (\underline{i}_{g,q,ref,+}^{\angle u_g} - \underline{i}_{g,q,+}^{\angle u_g}) - \omega_0 l \cdot \underline{i}_{g,d,+}^{\angle u_g} \quad (9)$$

The corresponding block diagram of the inner positive sequence current control loop of the inverter is given in Fig. 4.

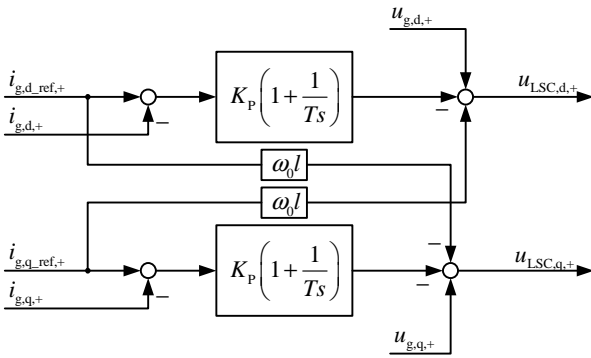


Fig. 4. Block diagram of the positive sequence current control

The dynamic setpoint for the positive sequence reactive current injection is calculated according to Fig. 5. In this block diagram the actual positive sequence voltage is compared to the pre-fault positive sequence voltage filtered by a PT1 element with time constant of roughly 60 seconds. In the voltage control block the gain of the reactive current injection and the dead band can be modified. The output is the dynamic positive sequence reactive current setpoint which is added to the stationary reference value.

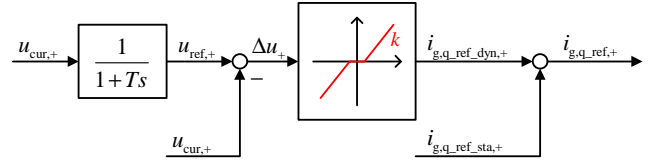


Fig. 5. Block diagram of the dynamic voltage control

In order to suppress the negative sequence current in unbalanced steady state or dynamic conditions the negative sequence grid voltage has to be detected and separated quickly. The space vector of the negative sequence voltage is rotating with the grid frequency in the opposite direction. The negative sequence space vector is described by equation (10).

$$\underline{u}_{g,-}^{\angle 0} = \underline{u}_{g,a,-} + j\underline{u}_{g,\beta,-} \quad (10)$$

The entire space vector of the grid voltage consists of positive and negative sequence components. Equation (11) describes the entire space vector in a stationary reference frame consisting of the positive sequence space vector and the conjugate complex negative sequence space vector.

$$\underline{u}_g^{\angle 0} = \underline{u}_{g,+}^{\angle 0} + \underline{u}_{g,-}^{*\angle 0} = \underline{u}_{g,+}^{\angle u_g} e^{j(\omega t + \varphi_u)} + \underline{u}_{g,-}^{*\angle u_g} e^{-j(\omega t + \varphi_u)} \quad (11)$$

Finally the output reference voltage of the inverter consists of the positive sequence reference inverter voltage introduced by (8) and (9) and the conjugate complex negative sequence grid voltage (10) and can be written as

$$\underline{u}_{LSC}^{\angle 0} = \underline{u}_{LSC,+}^{\angle 0} + \underline{u}_{g,-}^{*\angle 0} = \underline{u}_{LSC,+}^{\angle u_g} e^{j(\omega t + \varphi_u)} + \underline{u}_{g,-}^{*\angle u_g} e^{-j(\omega t + \varphi_u)} \quad (12)$$

The corresponding block diagram is introduced in Fig. 6 and represents the merger of positive sequence inverter and conjugate complex negative sequence grid voltage.

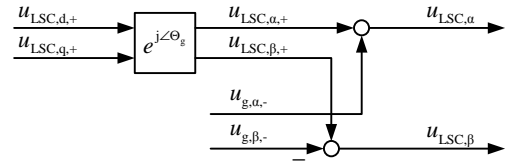


Fig. 6. Calculation of the reference inverter voltage

The basic sketch of the complex phasors of a three-phase PV inverter system is illustrated in Fig. 7.

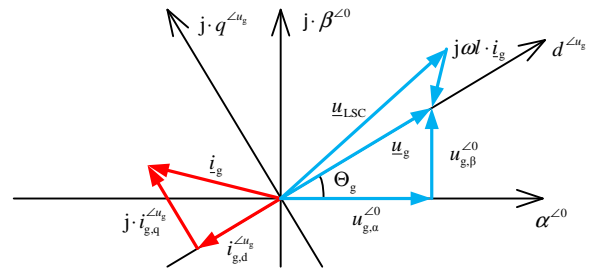


Fig. 7. Phasor diagram of the PV inverter system

4. PHOTOVOLTAIC POWER PLANT

The electrical behaviour of PV application basically depends on the control of the inverter system. Large scale PV power plants are equipped with a certain amount of central inverter systems. In this case study a test PV power plant with a nominal power of 3 MW equipped with 30 inverters and the corresponding PV array was simulated. Each inverter has a nominal power of 100 kW operating at the nominal voltage of 270 V and a nominal current of 214 A. For connecting these inverters from the low voltage (LV) level to the medium voltage (MV) level of 20 kV a three winding transformer is used. The primary winding of the transformer is delta connected while the secondary and tertiary are star connected. The total nominal apparent power of each transformer is 1.25 MVA while the short circuit impedance between the primary-to-secondary and primary-to-tertiary windings are both 0.12 p.u. Core saturation as well as the feeder cable of the low voltage connections are not taken into account (in this simulation study but may influence the behaviour during faults). Five inverters are connected in parallel to one low voltage terminal of the step up transformer. This means that the nominal total current in the secondary and tertiary windings is roughly 1 kA. The MV windings of the transformers are connected via a bus bar to the MV power system. The star point of the MV power system is directly grounded which has to be taken into account during unbalanced earth fault scenarios. Fig. 8 illustrates the schematic arrangement of the PV power plant.

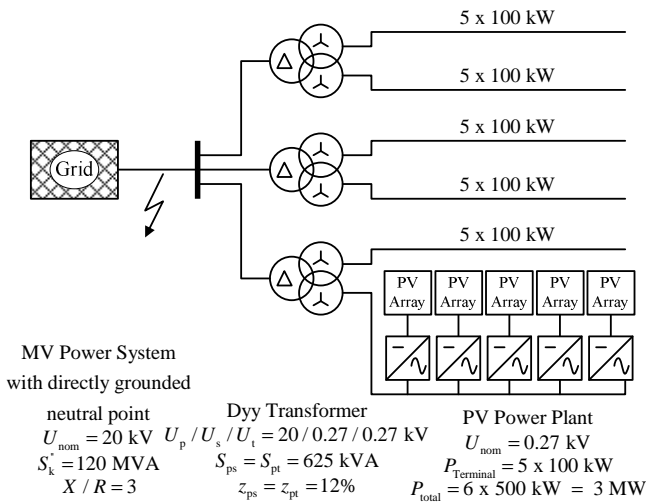


Fig. 8. Principle configuration of PV power plant

The location of the selected short circuits is between the MV busbar and the MV network. Three different fault scenarios were considered, namely a single-line-to-ground fault, a two-phase fault and a three-phase fault. All inverters were operating with nominal active power and a power factor of 1 at the medium voltage level prior to fault. So the inductive reactive powers of the three transformers are compensated by the reactive power control of PV inverters. The gain of the dynamic voltage controller of the inverters is set to 2 p.u. with a deadband of 0.1 p.u.

5. SIMULATION RESULTS

The EMT type simulation is performed using the software Matlab/Simulink, and realistic controller settings for the inverters are assumed. The duration of each fault is 150 ms, correlating with the standard fault clearance time in Germany.

Fig. 9 illustrates the behaviour of the generation units during a single-line-to-ground fault at the medium voltage (MV) bus bar. This unsymmetrical fault leads to a positive sequence MV drop of 0.33 p.u. while negative and zero sequence increase correspondingly to 0.33 p.u. Due to the vector group of the transformer the zero sequence of MV is eliminated at the low voltage (LV) terminal. The LV only consists of a positive and negative sequence component. Although the LV contains a negative sequence voltage the generation units are only injecting a positive sequence current during the disturbance. The positive sequence current is a capacitive reactive current due to requirements and its value is following the dynamic voltage control characteristic (Fig. 2).

The results of a two-phase fault at the MV bus bar are shown in Fig. 10. This unsymmetrical fault leads to a positive sequence MV drop of roughly 0.5 p.u. while only the negative sequence increases correspondingly to approximately to 0.5 p.u. The inverter systems are only feeding a positive sequence capacitive reactive current. This current is increasing the positive sequence voltage level at the low voltage terminal by some percent.

In Fig. 11 a symmetrical three-phase short circuit is described. The fault leads to a voltage collapse at the MV. The short circuit impedance of the transformer leads a residual voltage of roughly 0.1 p.u. at the LV terminal corresponding with the rated impedance of the transformer. Although the LV drops to only 0.1 p.u. the generation units inject a positive sequence current during the disturbance according to the voltage control characteristic. The injected positive sequence capacitive reactive current is limited to 1 p.u.

Regarding the short circuit contribution of the PV power plant in the presented three case studies, it is obvious that the generation units equipped with the corresponding control can only inject a positive sequence current fulfilling the timing restriction. Due to the missing requirements regarding negative sequence current injection during unbalanced grid faults the negative sequence current is usually suppressed to zero. It can also be seen from all three simulations that the inverter reduces the active current to zero during the short term disturbances due to the missing requirements for the active current injection in German grid codes.

In principle the PV inverters are able to supply more short circuit current during fault scenarios than only 1 p.u. reactive current due to current reserve margin of the inverter system. The control is able to limit the current injection during faults to the nominal but also to an overload current limitation of the generation system. Regarding the peak current during the transient periods of the faults the maximum peaks are slightly small and have a duration of only some ms.

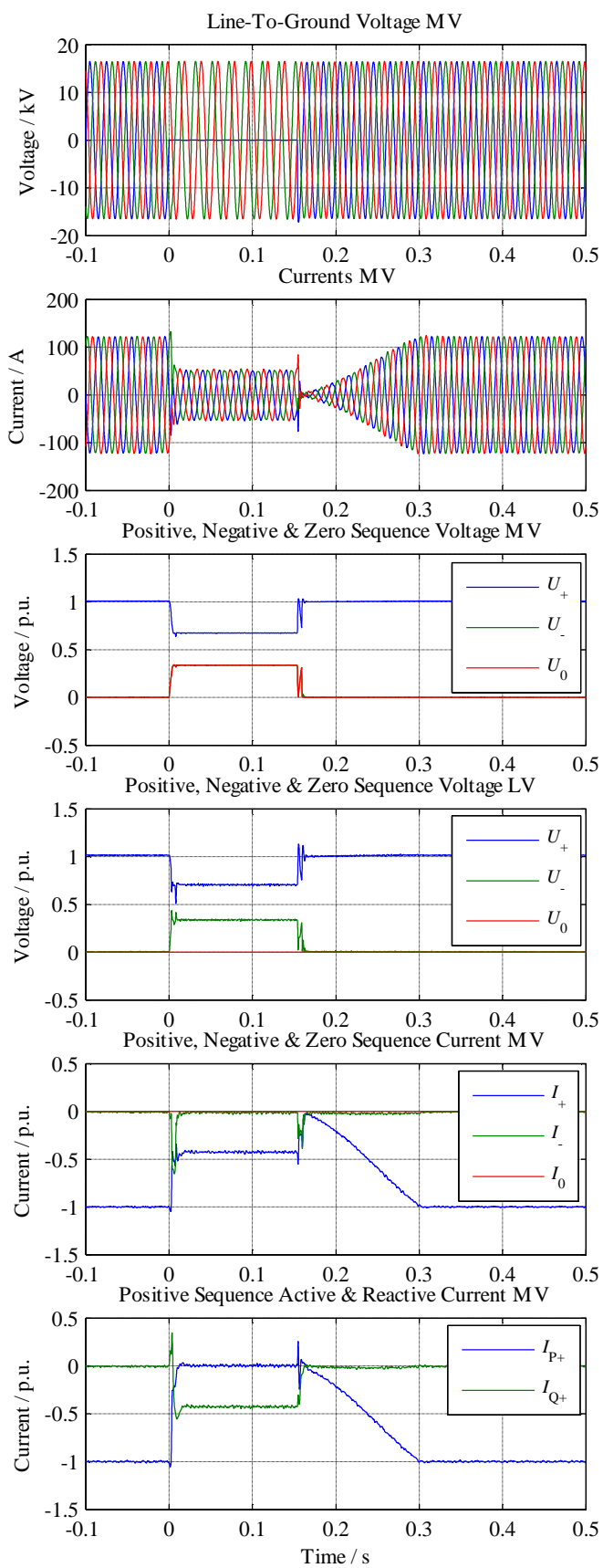


Fig. 9. Simulation results of a single-line-to-ground fault in the medium voltage network and the response of the generation unit

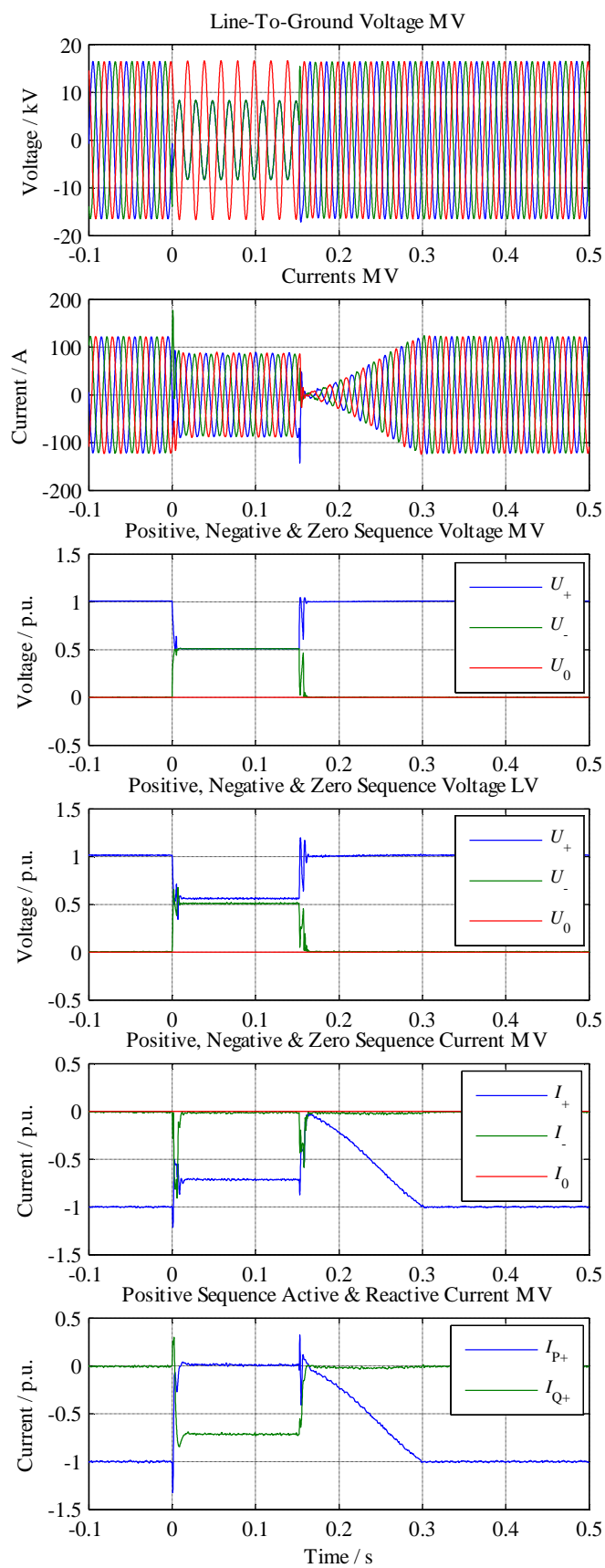


Fig. 10. Simulation results of a two-phase fault in the medium voltage network and the response of the generation unit

6. CONCLUSIONS

This paper has presented simulation results of the short circuit current contribution of a PV power plant to the MV power system under different fault scenarios. Due to the fast response of inverter control systems the behaviour of large scale PV applications is controllable even during the worst case fault scenarios. Consequently the current injection of PV and other renewable energy generation units differ from the response of synchronous generators regarding the peak currents as well as the steady state fault current.

Nowadays the positive sequence voltage support due to the injection of positive sequence reactive current has the control priority. Also nowadays the negative sequence current and the positive sequence active current is usually suppressed to zero by the inverter control. Regarding the control algorithms of the protection components in the power system the different behaviour of PV and other renewable energy applications may requires new protection concepts. The effects of a possible controlled negative sequence current injection of generation units on the power system is the subject of on-going investigation and the results will appear in future publications.

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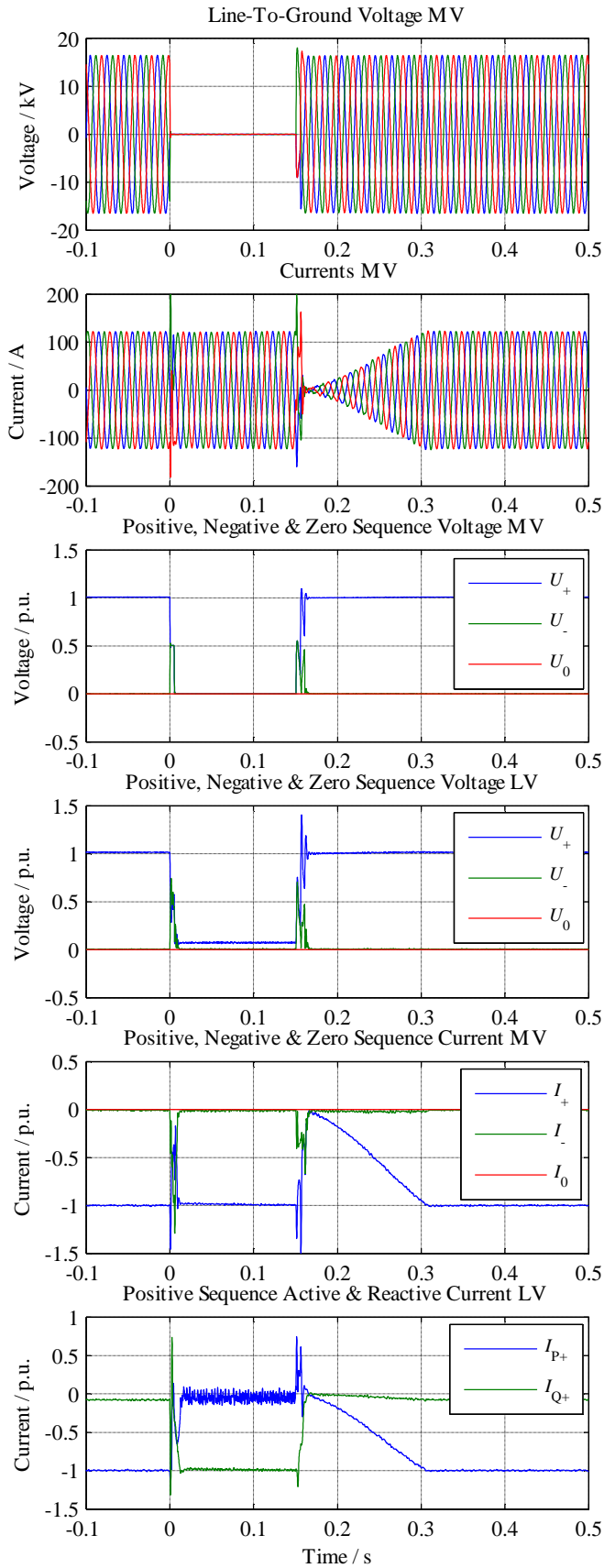


Fig. 11. Simulation results of a three phase fault in the medium voltage network and the response of the generation unit