Neutral Grounding in Wind Farm Medium Voltage Collector Grids

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Abstract— **The choice of the optimum neutral grounding option for a given network always involves a trade-off between the level of permissible short-circuit current on the one hand and tolerable voltage stress at the healthy phases following a single line to ground fault on the other. Effective grounding leads to high fault currents but the concomitant voltage stress is limited. The high fault current makes the fault detection and clearance easy. For conventional power transmission and distribution networks the available options are clear, and utilities have established grounding practices. But with increasing wind energy, it is necessary to take unique features of wind farms into consideration in choosing the most suitable neutral grounding option, at least for the wind farm grids. Based on EMT type simulation using a representative 144-MW wind farm grid, the paper provides an in-depth discussion of the pros and cons of the alternative grounding strategies vis-à-vis the relevant operational requirements within a large offshore wind farm, mainly focusing on the aspects of selectivity and voltage limitation. The level of over-voltages after tripping of the affected line for the feasible grounding options will be compared and contrasted with one another. Additionally, the effects of different voltage control strategies in the wind turbines on the over-voltages will be discussed and illustrated.**

***Index Terms*—Wind power, doubly-fed induction generator, grid codes, fault ride-through, voltage support, single line-to-ground faults, over-voltages, wind farm protection.**

I. Introduction

The choice of the optimum neutral grounding option for a given network always involves a trade-off between the level of permissible short-circuit current on the one hand and tolerable voltage stress at the healthy phases following a single line to ground (SLG) fault on the other. Effective grounding leads to high fault currents but the concomitant voltage stress is limited. The high fault current makes the fault detection and clearance easy. For conventional power transmission and distribution networks the available options are clear, and utilities have established grounding practices [1]. But with increasing wind energy, it is necessary to take unique features of wind farms into consideration in choosing the most suitable neutral grounding option, at least for the wind farm grids.

Wind power capacity increase in future will take place mainly offshore. Wind farms with several thousand megawatts are already in various stages of planning or implementation. The individual units within a wind farm are connected to one another via a medium voltage cable collector network, and the wind farms are then typically connected to the 400-kV onshore network through 150-kV-transmission-links.

As stated above, the choice of optimum grounding option for wind farm grids has to take several unique aspects of offshore wind farms into consideration [2]. These include first and foremost the offshore setting itself, which makes the cost of any repair or replacement of a submarine cable damaged by a fault significantly higher than a comparable task onshore and also the fact that any fault along the submarine cable can only be a structural non self-healing type. Additionally, wind turbines possess fast acting and increasingly sophisticated control systems aimed at improving their operational flexibility. As a result, wind turbines are required to provide voltage support at the point of interconnection to help stave-off possible loss of stability in a contingency situation. For the wind turbines providing the stipulated support functions during an emergency situation, it has to be ensured that internal faults within wind farms do not lead to tripping of the entire or even a considerable part of the wind turbines. The grounding option to be chosen therefore should be compatible and not work at cross-purposes with any of these requirements.

II. Wind Farm Collector System Topology and Grounding Options

A. DFIG based wind turbines

The DFIG is the most widely used generator system in modern wind turbines, since with its partial rated frequency converter in the rotor circuit it combines high flexibility with moderate costs. Fig. 1 shows the system configuration of a common DFIG-based wind turbine. The main components of the WT are:

- Rotor blades
- Gearbox (GB)
- Slip-ring induction generator (SRIG)

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- Machine-side converter (MSC)
- Line-side converter (LSC)
- Machine transformer (Tr)
- Filter (Filt) for reduction of switching harmonics
- Rotor-crowbar (CR) and chopper (CH) for converter protection

The main parts of the DFIG system are the Slip Ring Induction Generator (SRIG) with three-phase stator and rotor windings and the back-to-back PWM converter. The converter uses self-commutated IGBT switches and allows operation in all four quadrants. It is connected between the rotor circuit of the generator and the grid. The MSC operates at slip frequency and controls active and reactive power at the generator stator terminals. The LSC maintains the DC voltage and feeds the rotor power into the grid [3]. The direction of the power flow through the converter depends on the operating point of the generator. In sub-synchronous operation, the power flow is directed from the grid into the rotor circuit, while the power flow direction reverses in super-synchronous mode. Since the converter allows decoupled control of active and reactive power, the LSC can also be used for voltage support through reactive current in-feed in steady-state and during grid faults [4]. The distribution of reactive power flow between stator and LSC can be optimized for minimization of loss and/or thermal loads. Normally, during steady-state operation the LSC only provides a small reactive current contribution. However, during grid faults the current capacity of the LSC can be fully used to support the grid, because the response of LSC is faster than that of MSC.

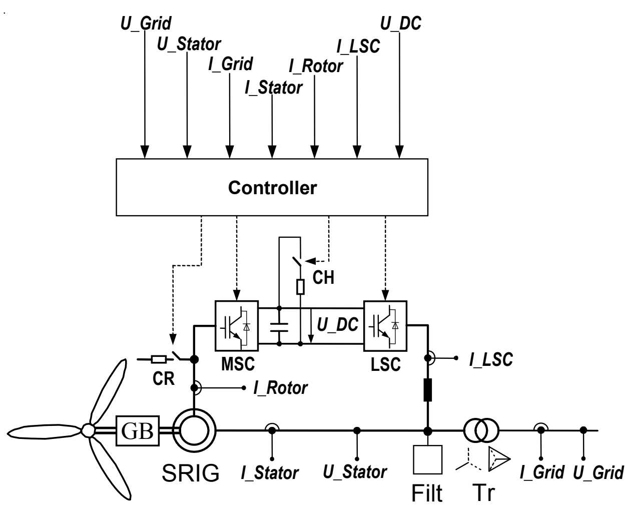

Fig. 1 DFIG-based wind turbine, main system components and measured quantities for converter control

The behavior of DFIG based wind turbines during grid fault differs from country to country, since the grid codes stipulate different behavior. Voltage support during grid faults, for example, is a requirement in the German grid codes, while in other countries like the US there is no such requirement and the WTs have only to ride through the fault without providing special grid support. This difference plays an important role in the behavior during internal WF faults, as will be shown in the simulation results.

Another important issue is the protection functionality of the frequency converter. According to the new German FRT requirements the chopper has to be designed to avoid a crowbar ignition for all faults that are not within the WT, making the MSC remain fully controllable during fault. Another important feature of the WT is the over-voltage protection of the converters. In the model used for this simulation the upper voltage level for tripping is set at 130%, which complies with most international grid codes. Since the disconnection of the WT by the circuit breaker may take over 100ms, the frequency converter has to block immediately once over-voltage is detected. With the IGBTs blocked, the stator remains connected until the breaker switches off. Meanwhile the machine draws reactive power and thus reduces the voltage.

Some manufacturers have implemented protection functions that recognize islanding of wind farms or parts thereof. However, reliable detection and separation from the grid may take a few hundred milliseconds, which is too long to protect wind turbines against over-voltages.

B. Type of grounding and its effect during fault

The purpose of this study is to investigate to what extent the neutral grounding in the medium voltage collector network affects the overall performance of the system during and following a single line to ground (SLG) fault.. Before the simulation results are presented and discussed, the available grounding options for transformer neutrals and their implications on the secure operation of the system in a general context are reviewed briefly [5].

1) Effective grounding

The level of fault current during a SLG fault is a function of the transformer zero sequence impedance (including the earthing impedance, if the neutral is accessible). The zero sequence impedance can also be influenced by selectively grounding some of the transformer neutrals. This option is the best from the grid point of view, but at the moment no off-the-shelf product from any of the wind turbine manufacturer offers this possibility. The fault current can thus be limited by using appropriately chosen grounding transformers. If the resulting overall zero sequence impedance leads to the voltage of the phase not directly affected by the fault being restricted to a value equal or below 1.4 p.u., the network is said to be effectively grounded. Effective grounding offers the benefit of fast fault detection (faster than 150 ms) and the possibility of selectively clearing the fault. On account of the short fault clearing time, the thermal stress at the fault location remains acceptable and only a small over voltage is experienced. Another advantage of effective grounding is that it requires lower isolation level.

2) Isolated neutral

A SLG fault current in this case may be too small to be detected, and, as a result, fast fault clearing is not possible. The excessive voltage stress with over-voltages reaching about 1.73 p.u. during fault would pose a danger to the whole grid. The transient voltage stress would also be relatively high. Due to all these reasons an isolated neutral is not recommended for the 33-kV collector wind farm grid. An apparent benefit vis-à-vis the enumerated disadvantages would be the fact that no grounding transformer would be needed in the 33-kV grid.

3) Compensation coil (resonant grounding)

The benefits of resonant grounding are well known, particularly in European grids. However, for a submarine cable grid these advantages do not come to bear. The relatively small fault current with a small ohmic part is not easy to detect and locate. This makes fast, selective fault clearance in the grid impossible although the fault is not self-healing. Additionally, during the fault the danger of a follow-up fault induced by the high earth fault factor, which can reach values of up to 1.73 p.u., is high. As opposed to the isolated neutral, this option would also necessitate an extra grounding transformer.

C. Wind farm topology – the current practice

A typical wind farm topology, which can serve as an example, is shown in Fig. 2. The offshore wind farm under consideration consists of 24 6MW wind turbines based on doubly-fed induction generators. It is separated into two groups, which are connected at the 33kV level to a three winding transformer. This transformer has a vector group of Ynd5d5 and connects the wind farm to the transmission voltage level of 150kV. The short circuit impedance between the two MV windings is selected very high to minimize the effect of internal faults in one part of the WF on the unaffected part.

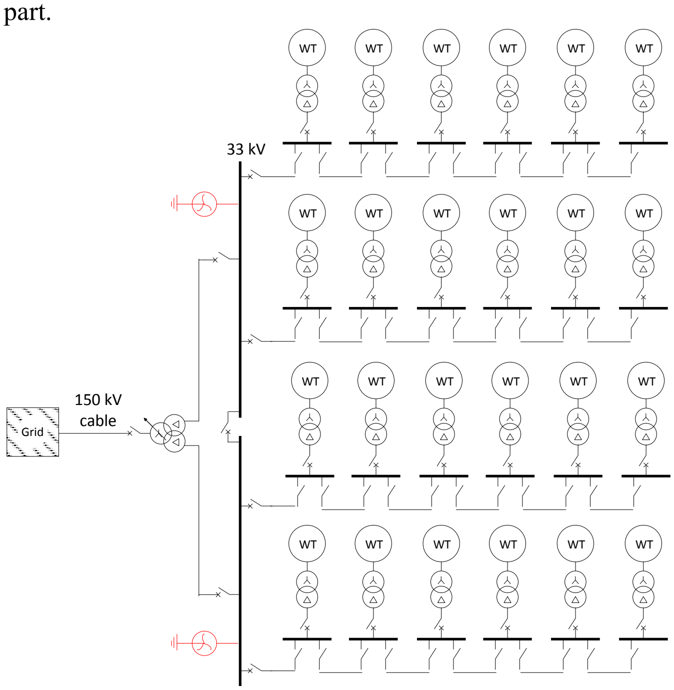

Fig. 2 Typical offshore wind farm configuration

Since the WF transformer (connecting the MV to the HV) has the connection Ynd5d5, no grounding option at the 33kV voltage level is available. Additionally, standard wind turbine transformers (connecting the generator to the 33-kV grid) are Dyn5 or Dyn5yn5 connected, again offering no grounding option at the 33-kV level. Considering the aforementioned restrictions imposed by the unavailability of standard equipment, the only possible grounding option in the WF grid can be provided by additional grounding transformers. Those are usually connected to the MV collector buses and located on the main substation platform. The grounding transformers contribute to the fault detection capability of the protection system during SLG faults and limit the maximum voltages in the healthy phases. On a general note, for the wind turbine transformer a change of the vector group to Ynd should be possible with some moderate effort, in the opinion of the authors.

III. Simulation Results

The simulation results presented here have been obtained using MATLAB/Simulink with SimPowerSystems Toolbox. The time domain simulations based on instantaneous values have been performed. The WT models used for this study have been developed in cooperation with wind turbine manufacturer and represent a very detailed generator and control structure. In the transformer models core saturation has been considered to account for its effect on the voltage. In some of the scenarios the WTs are provided with active voltage control according to the German grid code requirements [6]. This voltage control only acts on the positive sequence.

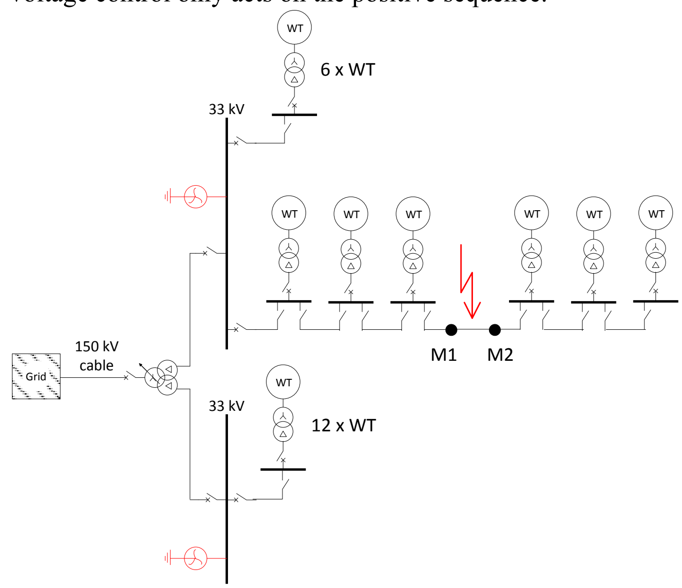

Fig. 3 Wind farm equivalents for EMT simulation including grounding transformers at collector bus

For reduction of the simulation time the wind farm topology has been simplified, using appropriate equivalents as shown in Fig. 3. Several scenarios have been simulated with different grounding and wind turbine voltage control strategies. The first two scenarios are based on the WF topology shown in Fig. 3. The simulated SLG fault occurs in the center of one branch between the measurement points M1 and M2.

In the first scenario the WTs do not have voltage control capability. The resulting voltages and currents at the measurement points M1 and M2 can be seen in Fig. 5.

Additionally, the symmetrical components of the voltages and currents are shown. During the fault the voltages in the healthy phases increases to a magnitude of approx. 42 kV, which corresponds to an earth fault factor of 1.55. The RMS value of the fault current at M1 in the affected phase is approx. 1.6 kA, which is within technical limits. Since the grounding transformer is located at the collector bus, there is no significant fault current at M2. Following the tripping of the affected branch at t=0.2 s, the wind turbines in this branch resort to an isolated operation without grounding and carrying considerable loads, i.e. the WTs try to continue feeding active power. Since no voltage control is implemented, a continuously increasing voltage can be observed. After approx. 50ms the voltages in the healthy phases approach a level of 260%, i.e. the line-to-line voltages at the MV side exceed the tripping level of 130% of the WT. In consequence the frequency converter blocks immediately and the WT circuit breaker will disconnect with a delay of approx. 100..200 ms. After blocking of the converter the voltage in the faulty branch is decreases to lower level.

In the second scenario the WTs are provided with active voltage control. Whereas during the fault the behavior is very similar to the previous case, after the tripping of the affected line, the voltage control leads to a completely different behavior (Fig. 6). After approx. 80ms the voltages in the healthy phases reach their maximum value of around 220% and then decrease again to 200%. This means a line-to-line voltage of slightly less than 130% at the MV side, which is below the tripping level of the WT.

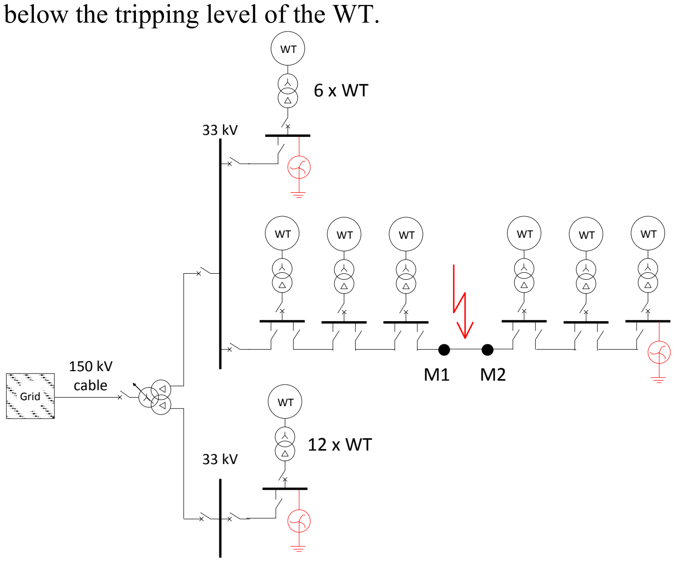

Fig. 4 Wind farm equivalents for EMT simulation including grounding transformers at the ends of branches

The next two scenarios are based on the grounding strategy shown in Fig. 4. Instead of placing the grounding transformers at the collector buses, they are placed at the end of the lines. As alternative to using extra grounding transformers, the neutral point of the WT transformer could be utilized for low-resistive grounding. As mentioned before, the currently used vector group for wind turbine transformer does not provide this option. However, in the opinion of the authors the change of the vector group to Yd with Y on the MV side would be possible without considerable effort.

The first scenario for this topology is again without voltage control of the WTs. The simulation results are shown in Fig. 7. During the SLG fault the voltages in the healthy phases are limited to a magnitude of approx. 40 kV with a corresponding earth fault factor of 1.45. Due to the lower earth impedance with two grounding transformers per MV grid section, the total fault currents become higher. However, the currents are distributed between the two paths. At M1 this leads to a maximum RMS current in the faulted phase of 2.3kA. At M2 the maximum RMS current is approx. 0.8kA in the faulted phase. After tripping of the branch, the voltage even drops initially and then increases to a value of 42 kV and remains at this level

The next scenario is based on the same topology as in (Fig. 4), but the WTs are provided with active voltage control. The results are shown in Fig. 8. During the SLG fault the only difference is that the active voltage controller supports the positive sequence voltage, which is slightly higher compared to the last scenario. After line tripping the voltage quickly reaches the settling value of 42kV in the healthy phases. In total, the differences to the scenario without voltage control are very small. In other words, the effect of voltage control after tripping of the affected line due to a SLG fault is negligible, when the grounding remains in the faulted branch.

IV. Conclusion

This paper has discussed the possible neutral grounding options for wind farm medium voltage collector grids under consideration of practical aspects. The simulation results show that only one grounding transformer at the collector bus bar allows reliable fault detection and tripping of the complete affected branch for SLG faults within the WF. However, after tripping, the faulted part remains as isolated grid with the WTs trying to continue feeding in active power to the grid. Without WT voltage control this leads to rapidly increasing voltage and finally to a blocking of the WT frequency converters and disconnection of the WTs. The maximum line to ground voltage in this case is approx. 260%. In the scenario with voltage control the voltage can be kept slightly below the tripping level of 130% in line-to-line voltages, i.e. the WTs will not be disconnected immediately but the line to ground voltage will increase up to 200% in the healthy phases. With the grounding transformer at the end of the branches, the over-voltages at the branch after fault-tripping can be limited to a moderately high value of approx. 155% of the nominal voltage. This is uncritical for the cable insulation. The influence of the voltage control is rather low in these cases.

As the main conclusion of the study, the authors strongly recommend providing neutral grounding in the wind farm collector grid even though the feeder is disconnected and the MV line including wind turbines remain separated from the grid following a fault. The high voltage stress on the cable following the SLG fault may result in consequential damages and thus high costs, in particular offshore. One option is using grounding transformers connected to the last WT in line. However, in the opinion of the authors, it would be more appropriate to use WT transformers with Y connection on the MV side (similar to the connection of generator transformers in conventional power plants), which would allow neutral grounding without additional cost. Besides, neutral groundings could be adapted to the number and location of WT in service.

Finally it should be mentioned that all strategies discussed in this paper can only provide limited protection selectivity, since the whole branch has to be tripped following a fault. A better, but more expensive protection, would be the use of differential relays for each line section. Then, the WTs could be connected in closed feeder loops and only the affected line would be disconnected during a fault, while all other WTs can continue operation. This would solve the over-voltage problems after tripping anyway and supersede the question of grounding transformer placement in the branches.

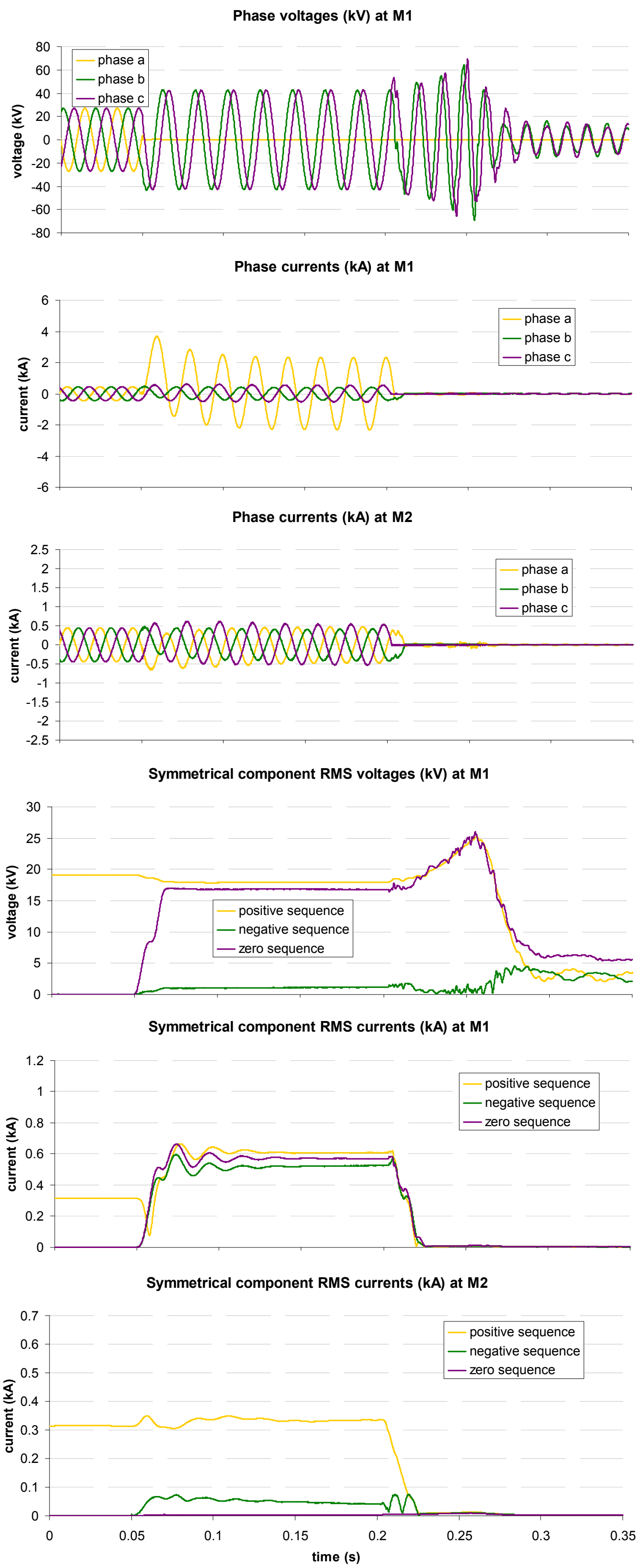

Fig. 5 Simulation results for a SLG fault with grounding transformer at the collector buses and WTs without voltage control.

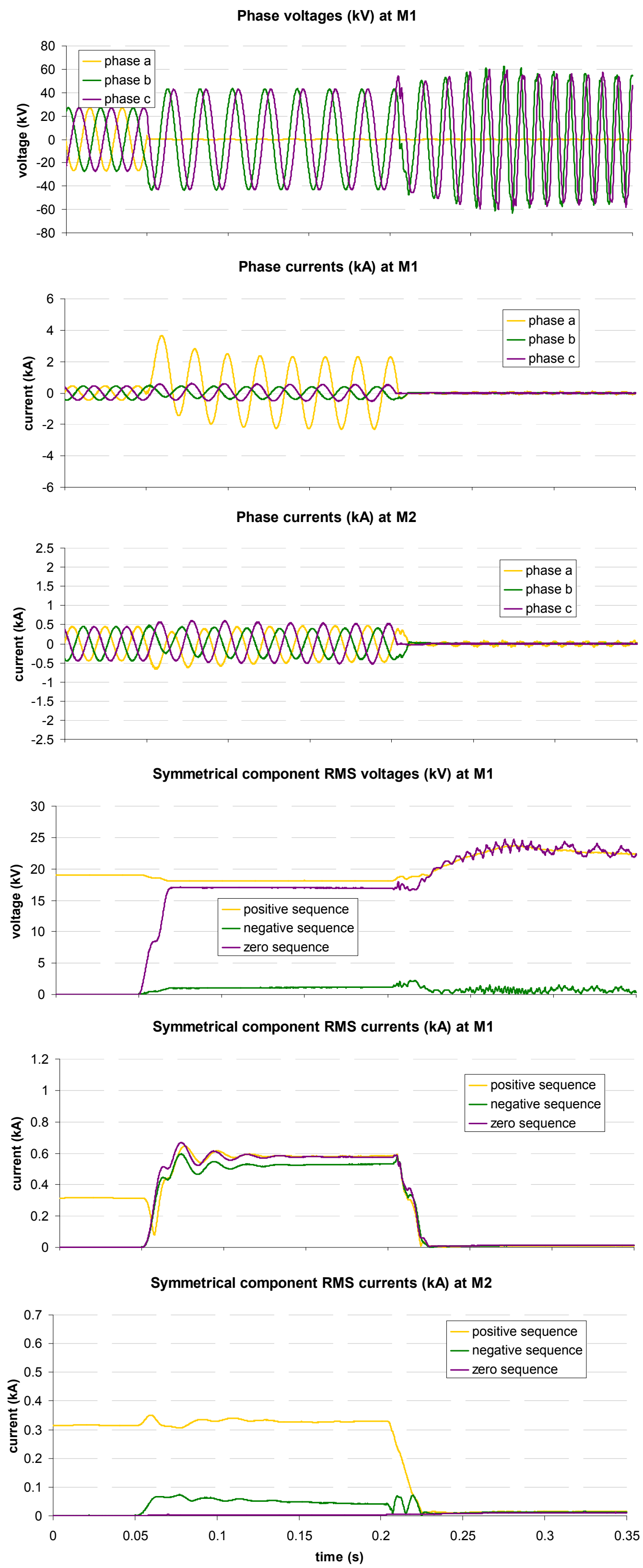

Fig. 6 Simulation results for a SLG fault with grounding transformer at the collector buses and WTs with active voltage control.

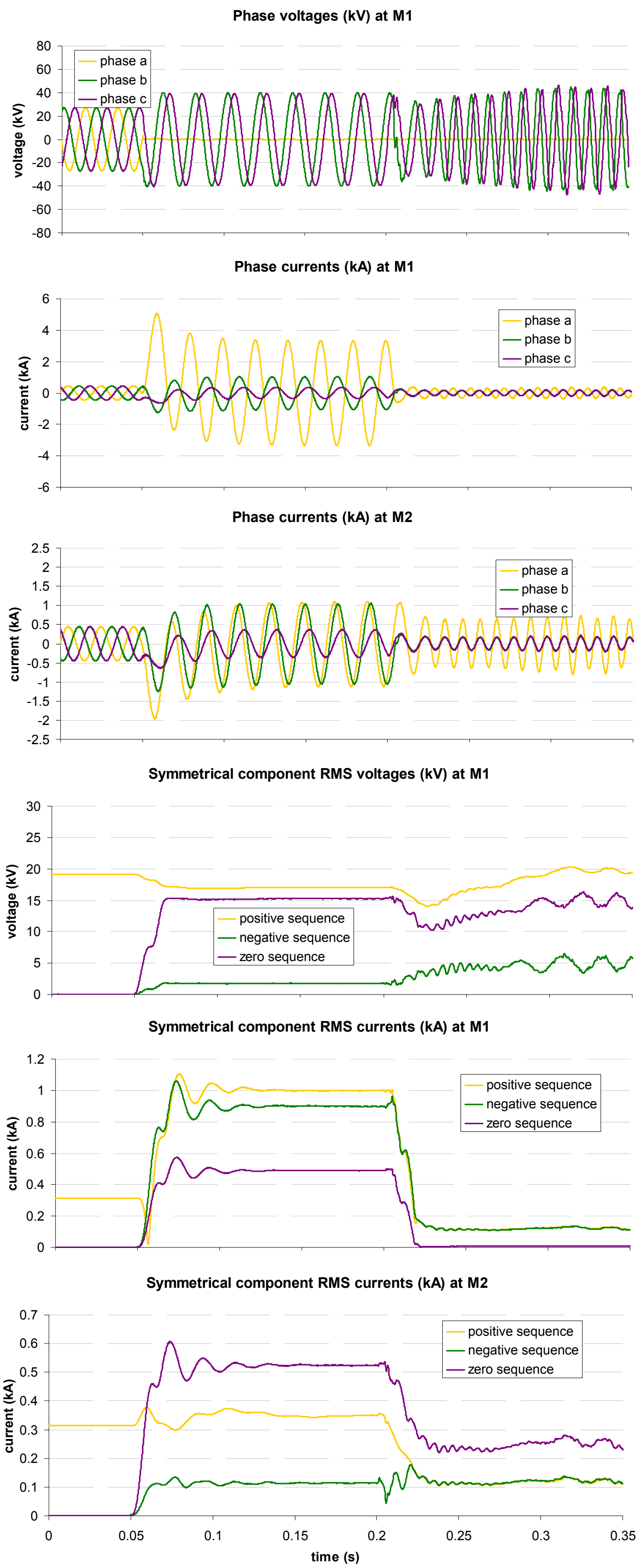

Fig. 7 Simulation results for a SLG fault with grounding transformers at the end of the branches and WTs without voltage control.

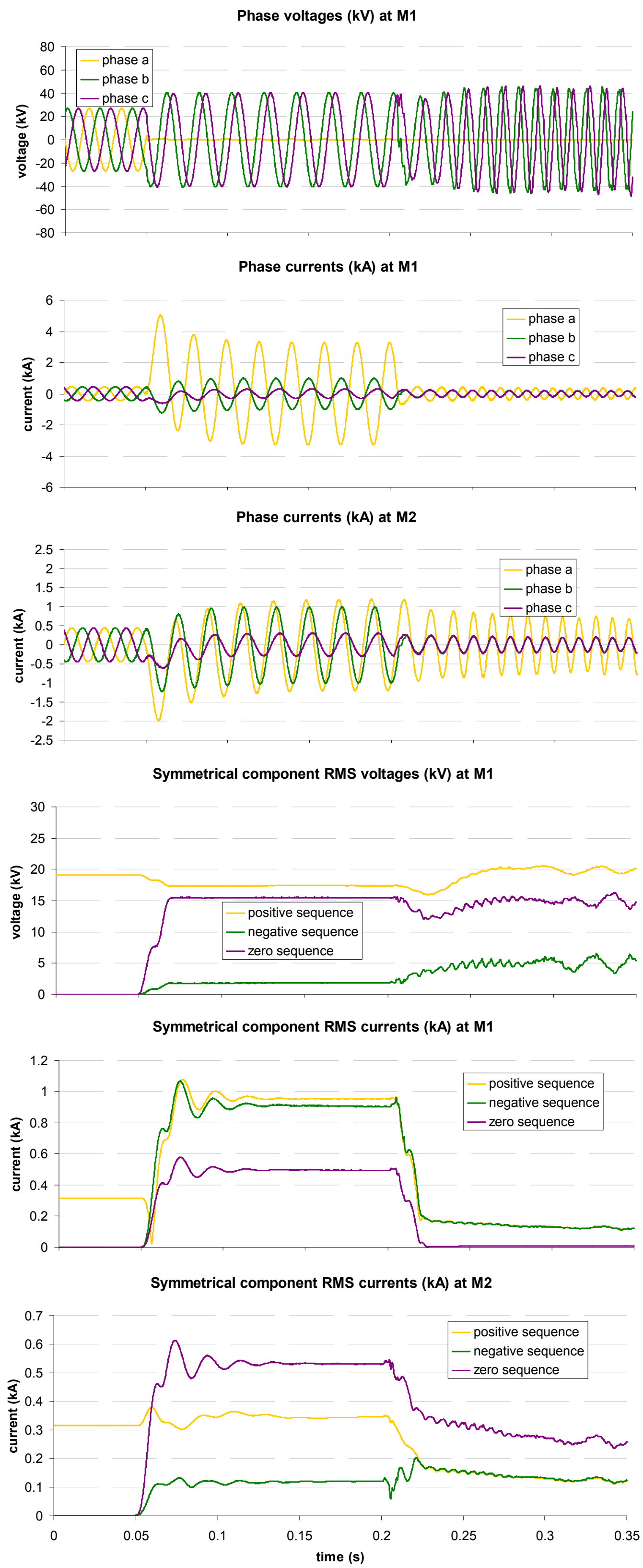

Fig. 8 Simulation results for a SLG fault with grounding transformers at the end of the branches and WTs with active voltage control.

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VI. BIOGRAPHIES

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