ASPECTS OF CONNECTING A SMALL-SCALE HYDROELECTRIC POWER PLANT IN AN MV DISTRIBUTION NETWORK - A SIMULATION STUDY

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ABSTRACT

In the paper the simulated results of connecting the asynchronous generator of a hydroplant to a medium voltage distribution system are utilized to find solutions to power quality problems caused by the starting and operation of these generators to the customers. Possible ways of increasing the power transmission capacity of medium voltage feeder are introduced. Aspects of earth fault protection with distributed generation are presented.

INTRODUCTION

In many cases the suitable locations for small-scale water-power investments are in remote rural areas, where the only possibility is to connect generators to the medium voltage (MV) network, which also includes loads. The main issue is that the initial costs of such an investment are low enough compared to the energy production capacity of the plant and power transmission capacity of the network. There are numerous suitable locations for this kind of small-scale water power investments in Finland and other Nordic countries.

Because the cost-effectiveness of the implementation is the crucial objective, induction generator (IG) based machinery which is not equipped with any hydro governor is used. No separate compensation capacitors are installed to compensate for the reactive power absorbed by the induction machines (IM). The continuous need for reactive power is fed by the power transmission system to which the primary substation is connected.

This paper introduces the electrotechnical problems inherent in the starting and network connection of asynchronous generators and possible disturbances to the MV system and customers connected to the same network. The earth fault protection of this type of distributed generation (DG) is also highlighted. The main research method is the dynamic modelling of asynchronous generators and MV distribution system including distribution transformers and loads. The case study is based on a real MV system and small-scale water power plants. The starting and steady state phenomena and their effects on the behaviour of the MV distribution system are simulated. The tool used in this research for analysis of the dynamic phenomena is PSCAD^{TM} [1].

TARGETS AND DESCRIPTION OF PROBLEM

The aim of the paper is to utilize the simulated results of connecting the asynchronous generator of a hydroplant to the MV distribution system to find solutions to power quality problems caused by the starting and operation of these generators to the customers. The main attention is focused on the hydroelectric power based on IG. The essential goal was to find out by simulations how the MV system respond to the instant need for reactive power caused by an initial magnetizing inrush transient of the IG when it is connected to the network. Special attention is paid to the effect of the instant reactive power with starting and steady state reactive power on the magnitude of voltages of the MV system. When the power plant is located electrically far away from the primary substation, there is also a problem of rising voltage.

An IG does not need synchronization with an electrical network, unlike synchronous machines. An isolated IG cannot produce terminal voltage as there is no source of reactive power to develop a magnetic field. Thus, when a de-energized rotating IG is connected to the network there is an initial magnetizing inrush transient followed by a transfer of real and reactive power to bring the generator up to its operating speed. The instant need for the reactive power and high starting current may cause voltage dips to the customers of the same MV system. For a large embedded IG the voltage transients caused by direct-on-line starting are likely to be unacceptable [2]. When an isolated IG is connected to the network the temporary supply of reactive power will be covered by the power transmission system. The objective of the study was to find out if it is possible to start IM based machinery without significant disturbances to network and customers with a 20 kV distribution system. The effect of the electrical distance of the IG from the primary susbstation on the voltage dips was studied. Attention is paid to aspects of earth fault protection and needs for novel developments.

The power transmission capacity of an MV feeder is not always adeqate which must be taken into account with network planning. One possibility to increase the transmission capacity is series compensation. The effects of series compensation compared to parallel compensation in the point of production are presented.

THE HYDROELECTRIC POWER PLANT AND THE ELECTRICAL NETWORK

The diagram of the hydroelectric power generator, MV network and the connections to the electricity transmission and production system of the appropriate case are presented in Figure 1.

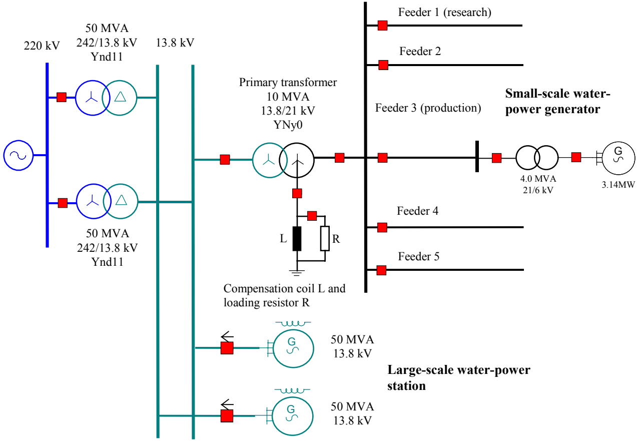

Figure1. Hydroelectric power plants, MV network and electrical transmission system.

The appropriate small-scale hydroplant unit considered in this study includes a 3.14 MW asynchronous generator which is powered by a Francis turbine with constant power. The generator is located about 9 km from the primary substation. The voltage of the IG is 6 kV and it is connected to the 20 kV system via a 21/6 kV transformer. The power factor of the IG is 0.88. The rated rotating speed is 1006 r/min and synchronous speed 1000 r/min. The runaway speed of the IG is 1.77-fold compared to the rated rotating speed. The rated current is 343 A and the starting current 1784 A. The MV network is fed from the 13.8 kV bus of the large-scale hydroplant (2*50 MVA). The loading of the production feeder (PF) is very low, maximum load being only about 0.15 MW. The reactive power for IGs is fed by the power transmission and production system to which the primary substation is connected. In addition to the real system, one additional feeder here named "research feeder" (RF) was modelled. The total length of the overhead line RF is 50 km. Utilizing the model of the RF the location of the hydro power generator and loading of the feeder could be varied. Detailed models of the PF and the RF include representation of lines between nodes, distribution transformers, loads and protection relays (O/C and E/F). The residual network was modelled as a background network with phase-to-earth capacitances for adjusting the earth fault current to correspond the actual value and load model for adjusting the total load of the MV system. Earth fault current compensation with compensation coil and loading resistor was also included in the network model.

Operation of the IM requires the voltage reaction of the network. They have no influence on the network until they are connected to it and the electrical countertorque develops. After network connection the output capacity of the generator is raised to the desired value by adjusting the rotative torque of the machine. This increases the absolute value of the slip of the asynchronous generator. In the case of hydroelectric power plant the rotative torque is controlled by changing the opening of the gate. The IG is connected to the network according to the measurement of the rotation speed. The rotation speed must be close enough to the synchronous speed. The induction generator is connected to the network when the rotation speed is about 97.5 % of the rated speed (100 %). After that it starts to generate power proportional to the rotative torque.

REACTIVE POWER ABSORBED BY THE ASYNCHRONOUS MACHINE

The interest focused on how the voltage at different locations of the MV system behaves during the starting period of the IG. The voltage dip at the connection point of the generator is one essential parameter. Also from the protection point of view it is important to know the magnetizing inrush current. The PSCAD^{TM} model of the IG (Fig. 1) was verified by carrying out measurements in the real system. The phase currents of the production feeder and the phase-to-earth voltages of 20 kV busbar were measured when the generator was connected to the network.

Connecting to the network

The following case concerns the situation when the asynchronous generator with rated power 3.14 MW is connected to the system defined in Figure 1. The soft-start unit or starting reactor was not in use with the simulations. The IG is connected at 2.0 s. In the simulation the power rise occurs in two seconds in order to keep the total simulation time reasonable. In practice the power rise takes several minutes. After the power rise it will be possible to observe how the production rate of the IG affects the steady state load flow situation of the MV system. Figure 2 presents the active and reactive power of the IG via circuit-breaker to the network during the starting period. Figure 3 illustrates the starting current at the moment of connection. The duration of the current impulse depends on the relative rotative speed of the machine in proportion to synchronous speed at the moment of connection.

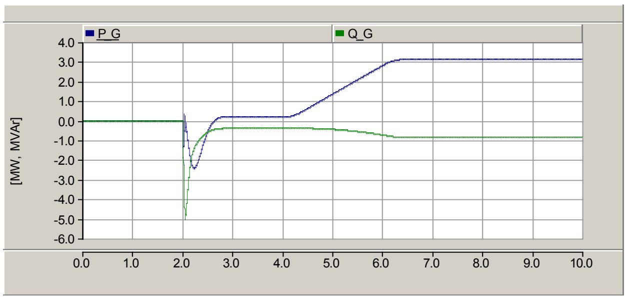

Figure 2. Active (upper curve) and reactive power from the IG to the network.

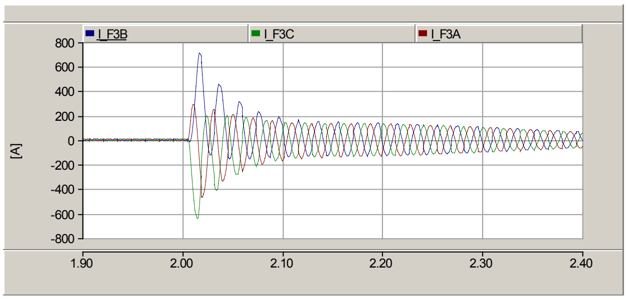

Figure 3. Phase currents of the production feeder (20 kV) when the IG is connected to the MV system.

If more than one asynchronous generators are located at the same power plant the total amount of temporary reactive power absorbed by the asynchronous generators can be reduced by connecting the IGs one at a time to the network and using a time delay between each connection. It is essential to know the acceleration time of the IMs for dimensioning the time step between generator connections. The acceleration speed depends on the rotative torque before connection to the network. If the acceleration is significant at the moment of connection only one machine can be connected to the network at just the right time, when its speed corresponds to the synchronous speed.

Voltage dips

The starting current may cause voltage dips to the customers of the same MV system. The following Figure 4 presents the voltage dips in the 20 kV busbar of the primary substation and the connection point of the IG when the 3.14 MW generator is connected to the system (Fig. 1).

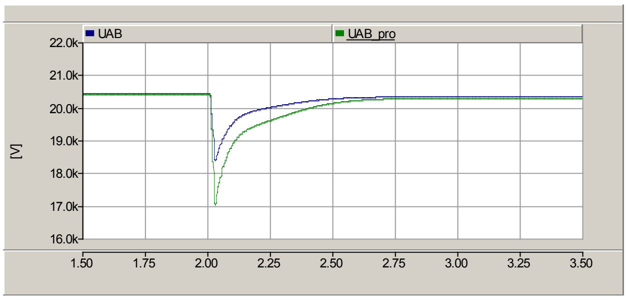

Figure 4. Voltage dips in the 20 kV busbar (upper curve) and at the connection point of generator (lower curve).

The shorter the electrical distance from a generator to a primary substation, the deeper is the 20 kV voltage dip at a susbstation. When the IG is electrially far away from a substation the voltage drops only slightly in the 20 kV busbar of the susbstation, but there is a deep voltage dip at a production point and behind it. The lowest voltage during the starting of the generator is achieved when the loading of the feeder is at maximum. The influence of these voltage dips will be distributed to other feeders where the magnitude and distribution of loads also affects the voltages.

LOCATION OF THE POWER PLANT

The location of power plant along the radial feeder has significant influence on the voltages in different parts of the feeder. In addition to production, a feeder normally includes loads. The relation of the production and loading of the feeder and the distribution of production and loads along it have a significant effect on the voltages of customers. Loads fluctuate depending on the time of day, season and customer group. Production may also fluctuate. Thus the relation of the load and production of the feeder varies. Typically, the cases affecting the dimensioning of the system are maximum load versus minimum production and minimum load versus maximum production. In the following study the modelled RF (Fig. 1) is utilized. The location of 3.14 MW IG and loading rate of the feeder were varied.

Effect on the voltages

Figure 5 presents the phase-to-phase voltages of the RF 0 km, 20 km and 35 km from the primary substation. The IG is located 35 km from the primary substation. It is connected to the network at 2.0 s and the power rise occurs at between 4 and 6 seconds. When the loading of the feeder is at minimum and the production at maximum, the voltage rise at the production point and behind it is the major factor affecting the network planning and dimensioning. The voltage dip in consequence of the starting can be limited using the soft-start unit or starting reactor limiting the starting current. In steady state the generator far from substation improves the voltages behind the production point during heavy loading of the feeder.

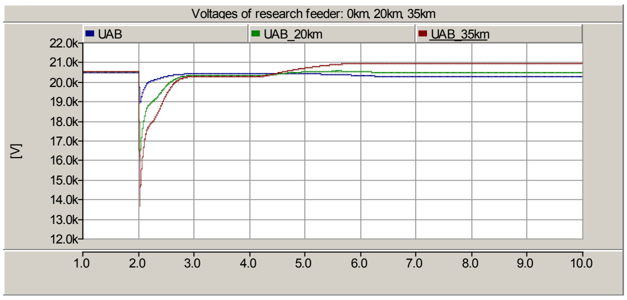

Figure 5. Phase-to-phase voltages of the RF during starting of the IG.

POWER TRANSMISSION CAPACITY AND COMPENSATION OF THE MV LINE

Typically the performance of long transmission lines can be improved by reactive compensation of the shunt (parallel) or series type. In the future the DG will be increasingly connected to the MV systems. One alternative for the reinforcement of a feeder is to use series compensation which normally is not applied in MV systems. Series compensation reduces the series impedance of the line, which causes voltage drop and is the most important factor in finding the maximum power transmission capacity of a line. When a production unit is located far from a primary substation along a weak distribution feeder, the voltage of the production point may rise too high. Series compensation is self-adjustable with regard to production and load variations. When an MV production feeder also includes loadings the difficulty may be where to locate the compensation unit. The wide variation of the ratio of the productive and load capacity along the MV feeder makes it difficult to locate the compensation unit at the optimal point. Normally it is reasonable to locate a compensation unit at the point where the sum power of a MV feeder is high. Series compensation brings a generator electrically nearer to the primary substation, which means that the voltages of the MV busbar are more affected by a high starting current of an IG. Behind the compensation point the residual voltage during starting increases due to series compensation.

IGs increase the transmission of the reactive power via the MV feeder considerably. Because the active productive power fulfils the need of the loading power of the feeder partially or completely, the transferred reactive power may even be the dominant power component in some cases. To improve the power factor it is reasonable in many cases to fit local power factor correction capacitors at the terminals of the generator. It is conventional to compensate for all or part of the no-load reactive power demand, although additional reactive power is drawn from the network. Thus, a parallel compensation has a quite small effect on the starting current transients of the IG. The parallel compensation mainly reduces the transferred reactive power and thereby increases the transmission capacity of the active power. Power losses of the line decrease. During light load condition of the feeder the voltage of the production point may rise too high.

EARTH FAULT PROTECTION

Short-circuit protection relates issues with a DG have been widely discussed and known, whereas the impact of DG on earth fault protection has rarely been analysed. The problematic impact of DG on system earth fault protection is caused by the ability of DG to sustain voltage during the fault and even after the tripping of the feeder breaker. Applying the autoreclosings with MV feeder including DG increases from before the need for the rapid earth fault indication of the DG unit. In the following problems regarding the earth fault protection of a DG with phase-to-earth faults in neutral isolated or compensated systems are presented.

The earth fault protection of MV feeders is normally based on measurements of zero sequence quantities. A distributed generator is normally connected to a network via a transformer with Dyn 11 or YNd 11 vector group. Thus zero sequence quantities generated by an earth fault of the MV system cannot be indicated on the low voltage side of a transformer (generator side). With larger hydro power generators a separate neutral voltage measurement on the high voltage side can be used to indicate an earth fault. In this case the tripping delays of the protection relays of the DG units must be coordinated with the tripping delays of the MV feeder protection in order to avoid unnecessary trippings caused by faults on adjacent feeders. Especially for the power balance situation back-up protection based on neutral voltage is advisable.

The anti-islanding protection of a generator is often based on over- or underfrequency. First a feeder protection trips a faulty feeder and a generator or generators remain for a short time to operate in isolation. Then the overspeed device trips the generator. Thereby the duration of the earth fault condition will increase. An isolated operation with a permanent earth fault is allowed in some cases if appearing touch voltages fulfill the safety regulations. Often the highest prospective touch voltages require rapid earth fault clearing. In this respect it must be remembered that with neutral compensated network the faulty MV feeder loses its connection to the arc suppression coil after tripping of a MV feeder. This can lead to the case that the fault current and thereby the touch voltage may even increase if the phase-to-earth capacitance of the islanded feeder is high. These facts emphasize the need to set strict requirements for anti-islanding protection of a DG unit.

Further development for earth fault protection will be needed due to described problems. One target of future development is that the earth fault protection of a DG against the network faults should be directional, in other words it should include the information of the faulty feeder.

CONCLUSIONS

The voltage dips during the starting period of an IG may be significant. In many cases applying the soft-start unit or starting reactor limiting the starting current is required. The location of IGs along an MV feeder significantly affects the voltages, the transmission of the reactive power and the dimensioning the feeder. Applying series or shunt compensation the conductor reinforcements can be substituted. The earth fault protection of a DG calls for novel developments.

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