

VOLTAGE STABILITY IMPROVEMENT BY STATCOM IN A WEAK NETWORK WITH WIND GENERATION

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Abstract: Nowadays electric power generation from wind energy as a renewable energy resource is under observation nowadays, due to existence of required technology and its economical aspects. Since the wind power is not controllable, induction generators are used in wind turbines. From voltage stability point of view these machines are reactive power consumers and have negative impact on system short term voltage stability. The impact of integration of a wind farm to test system is investigated in this paper by Voltage-Power studies and time domain simulation. STATCOM implementation has been proposed to improve short term system voltage stability with emphasize on installing location, control parameters and its capacity.

Keywords: short term voltage stability, wind power, FACTS, reactive power compensation.

1. Introduction

Recent reports indicate that wind generation is experiencing a fast growth all over the world in recent years. Installed wind power capacity reached 59GW by the end of 2005. These statistics had reach to 94.1GW at the end of 2007. Planting new wind installations in 2008 has 28.8 percent growth record. Total installed capacity all over the world reached 120.8GW and 158GW by the end of 2008 and 2009 respectively. USA, Germany, China, Spain and India have most installed wind capacity at present respectively [1-5].

Although there are different control strategies for wind turbines [6], but wind farms cause some problems in power system. Induction generator demagnetizes due to voltage dip during a short circuit fault, and rotor speed increases and generator delivers a large amount of reactive power to network. Active power delivered to the system will reduce at the same time and generator accelerates due to extra

energy from constant power produced by the turbine. After fault clearing, a large amount of reactive power will be absorbed by induction generator for rotor magnetization. This huge amount of required reactive power may cause voltage collapse [7, 8].

This paper also explains that increment of turbine generated power due to turbine shaft acceleration during fault will worsen this situation. By identifying instability modes using eigenvalue tracking by eigenvectors, induction motors and generators are reported responsible for short term voltage instability [9]. The effect of wind power on the transient fault behaviour of the power system is investigated in [10].

Protective measures aiming at minimizing voltage instability effects on part of the power system with more wind power penetration and minimizing wind power generation has been investigated in some literature. Precise tuning of overspeed and undervoltage protection of induction machines which are most prone to voltage instability aids in this object [9, 11]. References [11, 12] propose an undervoltage relay with a delay of few cycles to disconnect whole wind farm or partly. But the local thermal plant may trip due to inability to provide power demand after outage of large wind farms [13]. In the past years it was usual to isolate wind turbines from the network during a large disturbance and reconnect it after returning to steady state. But today and in the future wind farms should keep their continuous operation during network disturbances and support system's voltage and frequency [14]. Various requirements for fault ride through capability of wind turbines with defined voltage profile with reactive power and voltage limits has been defined [3, 15 and 16]. Older wind turbines without fault ride

through capability can be improved by some devices which provide this ability for the turbine (called “retrofitting”). Considering induction generator characteristics and voltage instability phenomenon, realizing this goal needs fast reactive power production with sufficient value at the proper location [3, 8 and 14]. So, theoretical and practical results of using FACTS devices are reported by different authors [3, 7, 13, 17 and 18]. Voltage oscillation decrement using STATCOM with a new controlling strategy is proposed in [19].

In this paper first a wind farm is connected to bus 10 of the study network, and V-P and V-Q analysis will be accomplished to study static voltage stability. Then short term voltage stability analysis is conducted by time domain simulations. Fast capacitor switching utilization and STATCOM implementation is investigated to confront with short term voltage instability the impact of STATCOM capacity, location and control parameters on voltage stability improvement is considered.

2. Test System Data

The test system shown in Fig.1 has been used in [9, 20 and 21] for voltage stability studies.

Total load in the network is 6000 MW and 1800 MVAR, and its generation is 6160 MW and has 2668 MVAR of shunt capacitive compensation. In order to increase wind generation penetration level in this network, total load and generation is reduced to one tenth of its base level. We have changed 500kv lines to 230kv standard type with the same length. This modification decreases reactive power support from line shunt suceptance and increases line impedance. The new impedance of line 8-9 is twice and its voltage level is half of the base level, i.e. 63kv. One of the 5 parallel 230kv lines is omitted to have a weaker system. Active power production of generators at buses 1 to 3 is 3566, 1500 and 1094 MW and reactive capacity of parallel capacitors at buses 6 to 8 is 868, 1500 and 300 MVAR respectively and all of them are reduced to one tenth. Load bus 7 has an industrial motor of 300 MW and bus 10 has a 300 MW compound commercial-residential load (half of static constant impedance and half of dynamic constant active power and constant reactive current). Bus 8 and 9 are linked via $0.24+j0.8$ ohm and bus 4 and 5 are connected via $j4$ ohm impedance. Hence, total load of this network is 600 MW and integration of a 100 MW wind farm to this network, will increase the penetration level of

wind generation to 17 %. Synchronous generators of buses 2 and 3 are of the 210MVA and 15.75kv round rotor in the “DigSilent Power Factory” software library. The wind farm is connected to bus 10. Two capacitor banks, one at the point of grid coupling and the other at the induction generators bus, are responsible to provide reactive power, maintaining zero reactive power exchange with the network at the steady state. Short circuit level at bus 10 is about 1000MVA.

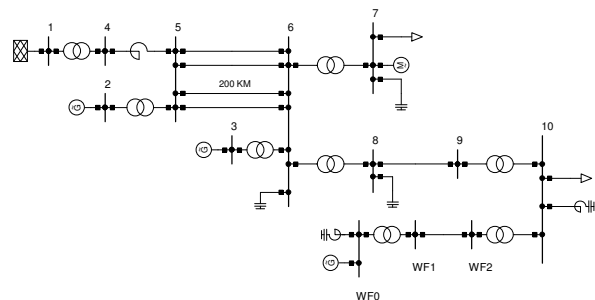


Fig.1 Ten bus test system with a wind farm at bus 10

3. Static Studies

To investigate the impact of wind farm integration on the 10 bus test system, V-Q and V-P analysis are used in the following. We don't change generators' load flow pattern here, as wind generation is added to system. But just reference bus active power decreases. All studies and simulations are accomplished by *DigSilent Power Factory* software.

3.1. Voltage-Active Power Curve Analysis

V-P analysis has been done by injecting active power to bus WF0 (by placing a negative load with unite power factor). Integration of a 20 MW wind farm is studied in this section. Buses 10 and WF0 are connected via 10km cables and two transformers with appropriate capacities. Power factor at bus WF0 is always 1 and it can be interpreted that all reactive power demand of induction generators is provided at that bus (installing large capacitors). The V-P curves are drawn in Fig.2 in two cases with and without the capacitor at bus 10, to illustrate the role of this capacitor, which is installed to keep unity power factor at point of grid coupling, and controls the bus power factor by inserting the capacitor in 1 MVAR steps during performing V-P power flows.

It can be seen that active power injection causes voltage increase in this bus. This is due to decrement of active power flow of line 8-9 and voltage increase at bus 10, which consequently leads to reactive power support provided by the wind farm cable

capacitance. In fact this overvoltage is the main reason that large capacitors are not installed next to induction generators. So it can be concluded that in this network wind generation integration can improve voltage at bus 10.

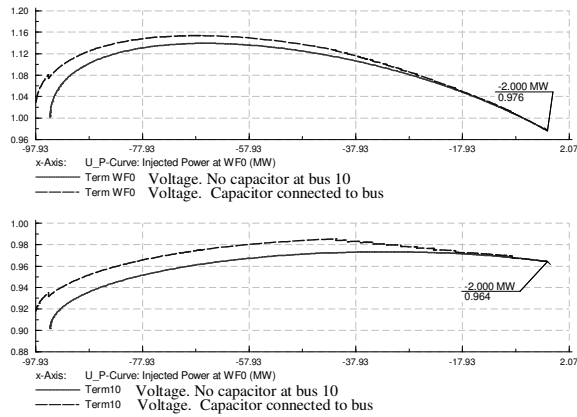


Figure 2- Voltage at bus 10 and WF0 while injecting active power to bus WF0 (The curve starts from -2MW with right to left direction).

In this case reactive power generation of local generator follows the curve in Fig.3 which shows that a specific increase in wind generation value, leads to an increase in local generator reactive power consumption by series components between bus 10 and WF0 and the consumption reaches 68 MVAR as shown in Fig.3. This analysis shows that integrating a 20 MW wind farm to this bus, has positive impact on voltage stability margin (due to local generator reactive power release) and voltage magnitude. However it will be shown in the following that this integration has negative impact, from transient voltage stability point of view.

When the cable length is 1 km, voltage at bus WF0 does not increase excessively, which verifies the fact that large series impedance (long electrical distance between bus 10 and WF0) and long cable capacitance cause this excessive voltage increment. In case of a 10km cable, voltage increase at bus 10 leads to an increase in wind farm cable capacitance reactive power generation.

The most important conclusion from this V-P analysis with different cable lengths, will be extracted from Fig.3. This figure shows that as the wind farm generation increase (with unity power factor) reactive power of local generator and bus 10 voltage increases. With increase of active power injection to bus 10 from -2 to -40 MW (X axis)

reactive power generation of local generator decreases from 20 to 7.5 MVAR.

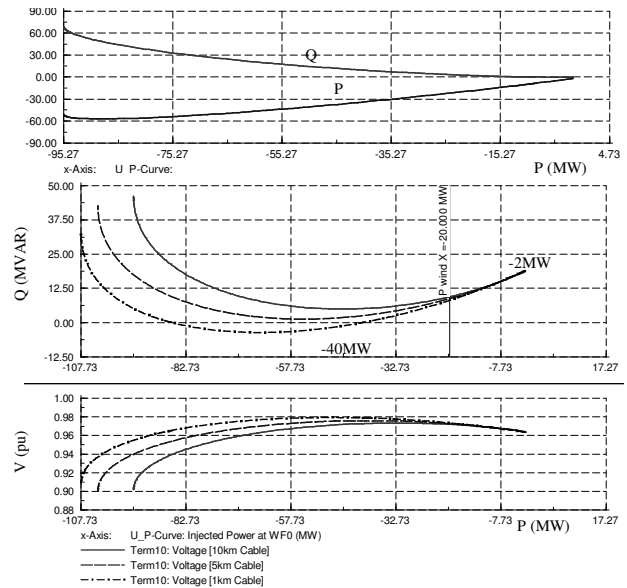


Figure3- Active power injected and reactive power absorbed by wind farm at bus 10 (up)-Local generator reactive power (middle)-Bus 10 voltage (down). All with respect to injected MW at bus WF0 for different cable lengths

Totally, it can be concluded from this curve that:

- There is no static voltage stability constraint for the wind farm at planned power production level (20 MW), since voltage collapse occurs at a level higher than 100 MW.
- Voltage magnitude improves when wind generation extends
- Local generator reactive power reserve increases when wind generation extends
- When cable length become shorter, the value of wind generation at which most reactive power reserve release occurs, increases (Minimum point of the curves at second part of Fig.3 moves down and left). It means that more wind power integration becomes more helpful.
- Series components at the wind farm path were chosen proportional to 20MW generation. If these components were extended, more positive effect will be achieved. Furthermore if the wind farm had unity power factor at the point of grid coupling, with the aid of a capacitor bank, more improvement in voltage and local generators reactive power reserve can be expected.

- At the planed production level (20MW), the value of growth in reactive reserve for various line lengths have not much difference and all are about 10 MVAR (the curves are coinciding at the start point).
- Decrement of cable length leads to increase in production capability.

These results show that active power provision at places near to load may lead to reactive power compensation.

3.2 Voltage-Reactive Power Curve Analysis

In order to find the value of required compensation and its importance, reactive power has been injected to bus WF0 with and without active power with different lengths of cable WF1-WF2. The results in Fig.4 show that when cable length increases, reactive power demand at the wind farm bus becomes a limiting factor of voltage stability. Nose point of the curves moves to right with the increase of cable length.

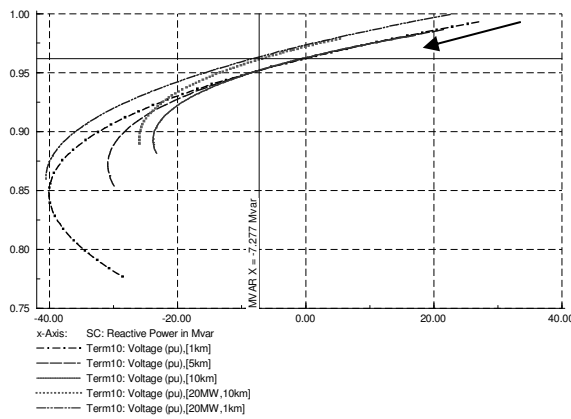


Figure 4- V-Q curve for bus 10. Reactive power is injected to bus WF0 with different cable lengths with and without active power at bus WF0.

As another conclusion, less reactive power is needed to keep the voltage at a desired level when there is 20 MW generation at bus WF0. It means that as active power generation increases, reactive power required decreases. For example when there is 20MW production at bus WF0, 7.277 MVAR reactive power should be absorbed, to keep bus 10 voltage at 0.96pu (see the dotted curve of Fig.4). But without active power generation there is no need to reactive power absorption or production to keep the voltage at 0.96pu. Again this is a consequence of flow reduction in line 8-9. Although the wind farm cable length is not selective, investigating these cases can

illustrate the effect of transmission and distribution system weakness on voltage stability.

It is underlined in [22] that voltage stability study in systems containing wind generation, needs implementation of detailed models of induction generators instead of PV or PQ models. So, in order to study the impact of induction generator's active and reactive power on voltage stability concurrently, for a 100 MW wind farm, here we increase the turbine power at 5 MW steps and run load flow in each step. To conduct this study the capacitors at bus 10 and WF0 are disconnected. Reactive power of the generator in this case increases from 30 to 60 MVAR. Considering P-V curves illustrated in Fig.5, it can be observed that like Figs 2 and 3 as produced power increases, voltage will grow up. Although the voltage at buses near to wind farm (WF0 and WF1) is less than bus 10 and WF2 at no load, but it is more than those one at full load. Results of Fig.5 verify the validity of the 3rd section results.

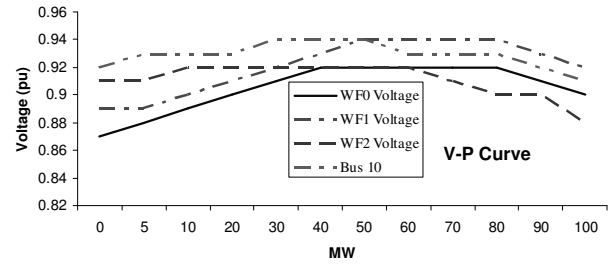


Figure 5- Voltage at different buses of wind farm with respect to produced active power.

4. Case Studies in Time Domain

Reduced model of wind farm is used in this paper, which means that a large number of wind turbines are modeled by an equivalent turbine with modified parameters. This model is appropriate for voltage stability study of a network considering a large wind farm and dynamic reactive power compensation [23]. The wind turbine model consists of mechanical model for shaft and turbine (aerodynamic efficiency) and induction generator model. The blades have constant angle during short term fault.

4.1. Base Case Study and Fast Capacitor Switching

As a definition, when the ratio of wind farm capacity to short circuit level of the bus is more than 15 percent, we have a weak network. Since the short circuit level at bus 10 before integrating wind farm is 1087 MVA, the system is to some extent weak to integrate a 100MW wind farm (with 120MVA

apparent power). But by integrating a 20MW wind farm to this system, we are not dealing with a weak system. The short circuit level at bus WF0 is 383 MVA. By considering half of the load at bus 10 as constant power the system will be more stressed from the voltage stability point of view.

According to explained short circuit levels and studies conducted at the previous section, a 20 MW wind farm does not induce any problem for static and short term voltage stability of the system. Time domain simulation also verifies this claim. Hence we integrate a 100 MW wind farm to this system. This test system is much similar to the simulated real case in [23], which has a 150 MW wind farm with short circuit level of 1800 MVA at the point of grid coupling. The simulations are conducted at three following cases by applying a three phase short circuit fault at bus 10 with 200ms duration and 0.25 ohm:

Case1: Before installing the wind farm

Case 2: After installing the wind farm with capacitor banks for no-Load reactive power consumption of the generator (installing more capacitors leads to overvoltage).

Case 3: Same as case2 with full compensation up to unity power factor at the point of wind farm grid coupling (bus 10).

Although steady state voltage stability margin extends after the wind farm is integrated to the system, and also local generator and 230kv lines absorb 30 and 8MVAR reactive power respectively when induction generator and its capacitors set are connected to grid, but definitely instability occurs at cases 2 and 3.

Three other cases are compared in Fig.6. The figure shows bus 10 voltage and induction generator speed during fault at that bus at case 1: (a) without wind farm, (b) with wind farm and capacitors at bus 10 without additional capacitor switching, and (c) with fast switching of additional capacitors at bus 10. To retain stability, two steps of 10MVAR capacitors should be inserted. Capacitor banks with thyristor switches (discrete control SVC) are able to insert the capacitor in less than one power cycle. Here the capacitors are tuned to keep unity power factor, with 200ms delay. Fig.6 shows that occurrence of a long duration fault leads to voltage instability even if all

reactive power demand of wind farm is provided at bus 10. Although the figure shows a voltage collapse, voltage collapse does not occur in this case, since the wind turbine will be disconnected from grid by its protection system. The wind farm does not lose its stability if such a distributed control system is implemented for all of the capacitors exactly next to the turbine at the wind farm, such that 12MVAR reactive power inserts at each step totally for all 50 wind turbines with 500ms delay time. In this case the capacitor is tuned to set the voltage between 1 to 1.05pu. But this kind of compensation is usually used at grid coupling bus or at the first bus which collects the generators' power. The results of inserting a 12 MVAR capacitor at bus WF0 with 0.5 second delay and also inserting two 10 MVAR step capacitor at bus 10 (to keep unity power factor) with 200ms delay are shown in Fig.7. If capacitor inserting at bus 10 is done slower, it can not retain stability, whereas connecting 12 MVAR is sufficient and it is effective, when the capacitor is placed at bus WF0 even connected with more delay.

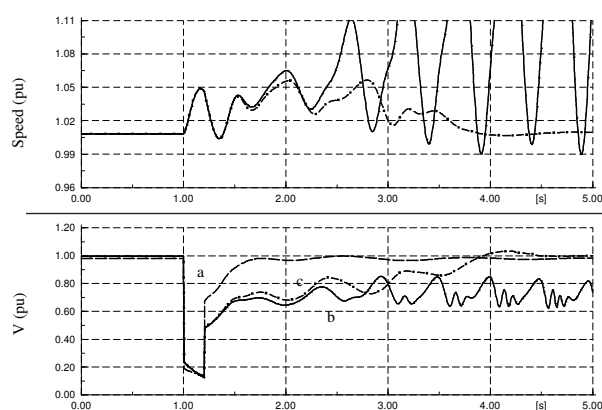


Figure 6- voltage at bus 10 and induction generator speed, (a) without wind farm (broken line); (b) with wind farm and power factor correction capacitors at bus 10 without switching additional capacitors (solid line); (c) with fast switching of additional capacitor at bus 10 (line with dot)

Figure 7 shows that even by fast inserting of large amount of capacitors at bus 10, the response of voltage and speed is worse than the case of 12MVAR capacitor at bus WF0 with more delay. If the power factor at bus WF0 is set to 1, voltage will reach 1.08 pu when cable length is 10km. So we had set the capacitor control to keep voltage less than 1.05 pu instead of a specific power factor value, and its capacity will be equal to no load consumption or the value that at the worst case does not cause overvoltage.

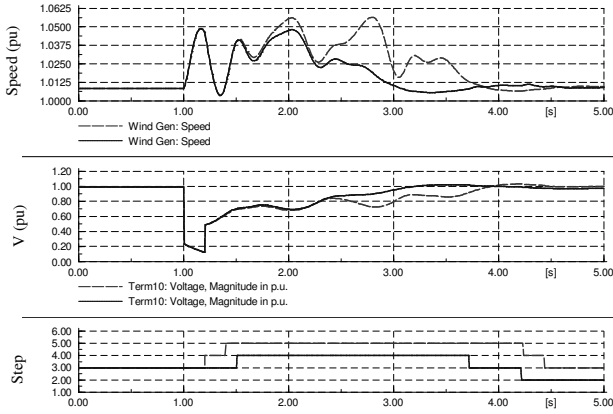


Figure 7- (a) Connecting one step 12 MVAR capacitor at bus WF0 with 0.5 second delay (solid line); (b) Connecting two step of 10 MVAR capacitor at bus 10 (to keep unity power factor) with 200 ms delay (broken line)

4.2. Dynamic Reactive Power Compensation

Reactive power of a capacitor is proportional to square of voltage, so its voltage-power relation is parabolic. So at voltage drops which reactive power support is more needed, reactive power production of capacitor seriously reduces.

As it is obvious from previous section the wind farm needs fast providing of reactive power to keep its stability. So considering the results of Fig.4 and the response of capacitor insertion from previous section and reactive power demand of wind farm, implementation of a 20MVAR STATCOM is proposed to deal with voltage drops and short term voltage stability problems. At the following section this capacity limit is refined, by performing simulations to obtain better results. The STATCOM model consists of external control with two PI blocks which samples ac and DC voltages and compares them with reference values. These voltages are implemented to control reactive and active current of the converter, respectively. The results of STATCOM installed at 4 different buses nearer to wind farm are extracted. In each case STATCOM voltage setpoint is tuned such that no reactive power exchange to the grid exists at the steady state.

4.2.1 Comparison for Installing at Different Buses

Although proper proposed capacity for STATCOM was 20MVAR, but we have selected two limited cases to study the effect of additional short term capacity on induction generator stability. At the first case, STATCOM is able to inject 2.67 time of its nominal capacity at sever voltage drops. At the other case this ability is just 1.1 time of nominal capacity. Internal current controller parameters of Fig.8, which

controls reference signals provided by external controller, are modified such that to make the possibility to inject current more than nominal value during fault (non-optimal parameters). In this figure I_d , I_q , P_{md} and P_{mq} are current component of dq reference frame and modulation indices of the converter respectively. In this way, four control cases of STATCOM appear: 1.1 times limited with non-optimal parameter setting (type 1) or optimal parameters (type 2) and 2.67 time limited with non-optimal parameters (type 3) or optimal parameters (type 4).

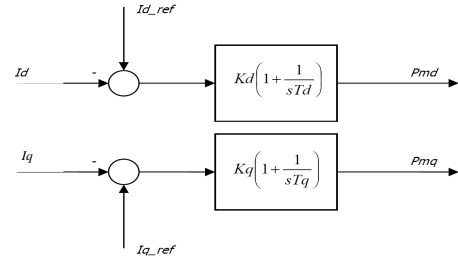


Figure 8- Internal current controller of STATCOM

Voltage at bus 10 and induction generator speed curves are drawn in Fig.9 for “type 2” case. These two variables are good criteria to investigate how short term voltage stability improves. This figure shows that installing STATCOM at bus WF0 is better than WF2 and it can recover voltage faster in spite of injecting less reactive power. This conclusion can be obtained by comparing the area surrounded between the two curves.

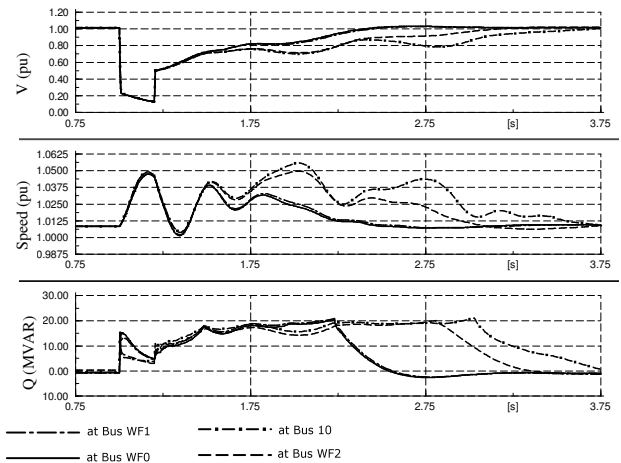


Figure 9- Voltage at bus 10, induction generator speed, and STATCOM reactive power for type 2 controller at different buses.

If the current capacity limit is increased to 2.67pu, the results will improve significantly, but their order is same as 1.1pu limit (buses WF0, WF1, WF2 and

10 have better results respectively). If non-optimal controller parameters are used, the STATCOM injected current will be more than permissible value during fault but the order of the results does not change.

Installing STATCOM at bus WF0 has lead to more reactive power injection during fault. So it prevents the generator to accelerate which reduces mechanical stress on the turbine. At all 4 studied control type cases, buses nearer to induction generator were more appropriate for install and the results for bus WF2 were always better than that of bus 10 since large reactance of the transformer between these two buses consumes some wind farm absorbed reactive power.

4.2.2 Comparison of Different Controls at a Bus

Buses WF0 and WF1 are integration of 50 buses and obviously installing STATCOM at all of them is not possible. Furthermore Fig. 9 shows that installing at bus WF2 is much better than bus 10. With these two reasons, comparison for controller type is just performed for bus WF2. The results when STATCOM is connected to bus WF2 are drawn in Fig.10.

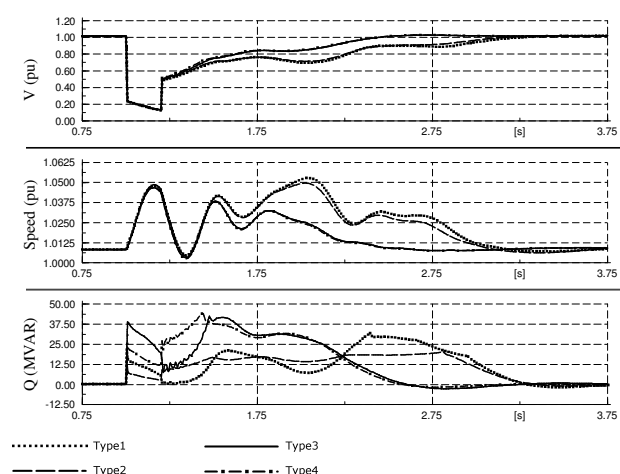


Figure 10- Voltage at bus 10, induction generator speed and STATCOM reactive power when STATCOM with different controllers is installed at bus WF2.

It can be concluded from Fig. 10 that in the case of having 1.1 pu limitation (type 1 and 2) using optimal parameters is better, which means type 2 is better than 1. But in the case of having 2.67pu limitation (type 3 and 4) using modified parameters is a little better, which means type 3 is better than type 4, since it injects more reactive power during fault. It can be concluded that when the compensator capacity is

limited, accurate tuning of controlling parameters is more important, the subject always important.

The results of Figs.9 and 10 shows that bus WF2 is the best location for STATCOM installing and 20 MVAR capacity is sufficient.

4.3 Investigating STATCOM Capacity Limitation

If STATCOM capacity limit is 1.35pu on 20MVAR base and it has optimal controller parameters, it will be able to keep voltage stability even for two contingencies; i.e. a short circuit fault at bus 10 and a 230kv line outage 0.9 second after the first fault. But when this capacity limitation is decreased just 0.05pu and reach 1.3pu, then the wind farm will be unstable.

5. Conclusions

This paper carefully investigated the impact of wind farm on voltage stability of a power system and its short term voltage instability improved by STATCOM. Proposing a pattern for STATCOM capacity determination considering the impact of control parameters and installation location by implementing time domain simulations is the strength of this paper. Following results are obtained after wind farm integration:

1) Static voltage stability improves, 2) Grid faults causes wind farm instability and extension of the instability to system, 3) To prevent instability, fast provision of sufficient reactive power is needed, 4) To determine STATCOM capacity, reactive power requirement of wind farm during fault condition should be considered, 5) If implemented power electronic devices were able to sustain more than their nominal current value for less than 1 second (i.e. 2.7 pu instead of 1.1 pu) then significant improvement of short term voltage instability could be obtained.

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