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Evaluation of the suitability of a fixed speed wind turbine for large scale wind farms considering the new UK grid code

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Abstract

The analysis of the reactive power management of a wind farm consisting of fixed speed wind turbines is carried out. The rating calculation of the compensator for a fixed speed wind farm is evaluated, and the effect of the network strength on the compensator rating is studied. Also the compatibility of fixed speed wind turbine with the new UK grid code requirements is evaluated by simulation using Matlab/Simulink. The simulation results show that the compensator rating is mainly determined by the need to meet the grid code specifications, rather than the steady state reactive power capability obligation. The main conclusion is that a fixed speed wind farm based on simple induction generators is unable to meet the new grid code requirements, unless the compensator rating is increased substantially.

Keywords: Wind energy; Fixed speed wind turbine; Induction generator; Grid code; Short circuit ratio; STATCOM

1. Introduction

Wind turbine technology has undergone a dramatic transformation during the last 15 years, developing from a fringe science in the 1970s to the wind turbines of the 2000s utilizing the latest in power electronics, aerodynamics and mechanical drive train designs.

Worldwide, by the end of 2006 there were many thousands of wind turbines in operation, with a total capacity of 73.904 GW. In the UK, about 1.963 GW of wind generation was in operation by the end of 2006 [1]. The target for UK electrical energy to be supplied by renewable forms of generation by 2010 is 10% of the total electricity demand. This target implies a total renewable generating plant capacity of up to 10 GW, of which some 60% might be wind turbines [2].

Induction generators are more attractive than synchronous generators for wind turbines due to their robust construction, low cost, low maintenance, long life (more than 50 years) and low power to weight ratio [3]. However the reactive power management is a major concern, not only to compensate for the reactive power requirements of the wind farm itself but also to support the system voltage in particular for wind farms based on fixed speed induction generators.

In the past, there was no requirement by the grid code for a wind farm to remain connected to the grid during a fault or a voltage disturbance. The protection of the wind farms has mainly been focused on turbine protection without considering the impact it might have on the power system. This implies that the wind turbine is disconnected from the grid as soon as a violation of voltage or frequency operating limits is exceeded.

However, increasing wind power penetration means that wind power plants have to behave more like conventional power plants and hence have to take over many of the control tasks that hold the power system stable. The requirements for the connection of wind farms to electrical network are defined by the new connection code [4].

The grid connection requirements vary in different parts of the world, but they have common aims: to permit the

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development, maintenance and operation of a coordinated, reliable and economical transmission or distribution system. The new requirements generally demand that wind farms provide additional services, such as steady-state and dynamic reactive power control and/or voltage control, to support the network to which they are connected.

In this paper, finding of an investigation into the steady-state and dynamic operation of a wind farm based on fixed speed induction generator with a STATCOM is reported. Also the effect of the short circuit ratio (SCR) at the point of connection on the compensator rating is studied. Particular emphasis was given to the compliance with the UK grid code [5]. The study was carried out by means of simulation using the software package Matlab/Simulink.

2. Grid code requirements for wind farm connection

Worldwide, the new grid connection requirements have identified three areas to be considered in the operation of wind farms; voltage and reactive power control, fault ride through capability and frequency range of operation.

2.1. Voltage and reactive power control

In general, wind farms have to be able to afford automatic voltage control at the point of connection by continuous control of the reactive power at their terminals, according to a certain characteristic specified in a site specific bilateral agreement. In the UK, the general reactive power capability requirement of a wind farm is defined in Section CC.6.3.2 in the UK grid code [5] (see in Fig. 1). The wind farm must be capable of supplying rated MW output at any point between the limits 0.95 power factor lagging and 0.95 power factor leading at the point of connection with the GB transmission system.

From the UK grid code, with all plant in operation, the reactive power limits defined at rated MW at lagging power factor will be valid at all active power output levels above 20% of the rated MW output as defined in Fig. 1. With all plant in operation, the reactive power limits defined at rated MW at leading power factor will be valid at all active power output levels above 50% of the rated MW output as defined in Fig. 1. With all plant in service, the reactive power limits will reduce linearly below 50% of active power output as shown in Fig. 1 unless the requirement to maintain the reactive power limits defined at rated MW at leading power factor down to 20% active power output is specified in the bilateral agreement. These reactive power limits will be reduced pro rata to the amount of plant in service. The reactive power limits for active power output below 20% shall be adjustable within the area of $Q = -5\%$ of rated MW output to $Q = 5\%$ of rated MW output [5].

2.2. Fault ride through capability

Voltage swing and power oscillations must not result in the triggering of the generating unit protection. The wind turbine generator shall be equipped with voltage and frequency relays for disconnection of the wind farm at abnormal voltages and frequencies. The relays shall be set according to agreements with the regional grid company and the system operator [6].

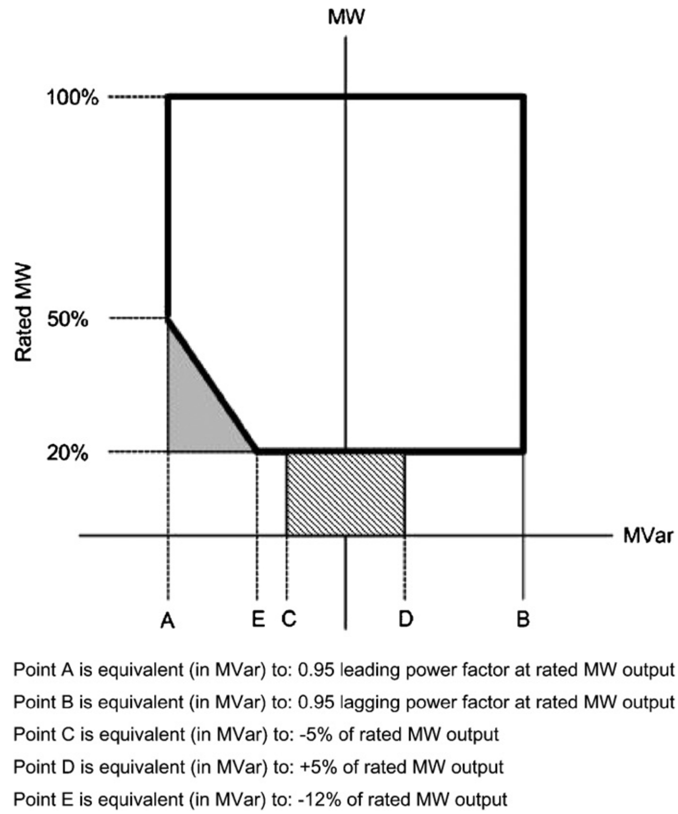

Fig. 1. Required reactive power capability of wind farms. (Fig. 1 of connection conditions of the grid code [5])

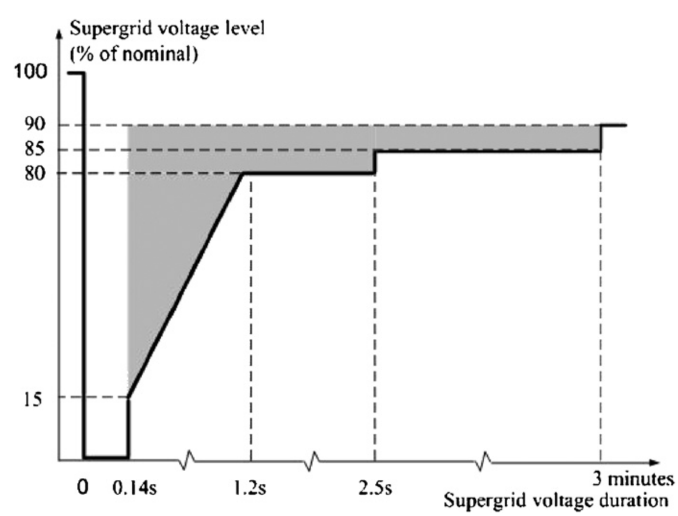

Fig. 2. Required ride through requirement for UK.

The voltage characteristic of fault ride through requirement of a wind turbine is defined by a minimum voltage throughout the duration of the fault followed by a ramping up with a given slope to the nominal level as the voltage recovers. Each country has its own fault ride through capability chart. Fig. 2 shows the UK fault ride through capability chart, as defined in Section CC.6.3.15 in the UK grid code [5]. From Fig. 2, it can be inferred that the wind farm shall stay transiently stable and connected to the system without tripping for a close-up solid three-phase short circuit fault or any unbalanced short circuit fault on the transmission system with a total fault clearance time of up to 140 ms. During the operating range of the wind farm, these types of faults must not result in instability or isolation from the network. For supergrid voltage dips of duration longer than 140 ms, the wind farm has to remain connected to the system for any dip duration on or above the heavy black line in Fig. 2. For system faults cleared within 140 ms, upon the recovery of voltage to 90% of nominal, a wind farm has to provide active power to at least 90% of its pre-fault value within 0.5 s. For voltage dips of duration greater than 140 ms, a wind farm has to supply active power to at least 90% of its pre-fault value within 1 s of restoration of voltage to 90% of nominal. It should be noted that in cases of less than 5% of the turbines in operation, or under very high wind speed conditions where more than 50% of the turbines have been shutdown, a wind farm is allowed to trip [5].

2.3. *Frequency range of operation*

The design of generator plant and apparatus must enable operation in accordance with a certain frequency range specified in the grid code of each country. For example, according to the frequency requirements in the UK grid code (Section C.C.6.1.3), wind farms are required to be capable of operating continuously between 47.5 and 52 Hz and at least 20 s for system frequencies between 47 and 47.5 Hz. This is a relatively wide range in relation to realistic events [5].

3. Reactive power requirement of fixed speed wind turbine

Fixed speed wind turbines basically consist of squirrel cage induction generators which are directly connected to the grid via a step-up transformer. Traditionally, the required reactive power for the machine excitation is provided by the capacitor banks installed at its terminals. However, capacitor banks cannot provide dynamic compensation for events such as the sudden drop of voltage [7]. Dynamic compensation devices such as static VAr compensator SVC, or static synchronous compensator (STATCOM) can provide a suitable compensation for fixed speed wind farms [8].

In the studies reported in this paper, a STATCOM was used to provide the reactive power required by a 60 MW fixed speed wind farm. In order to reduce the STATCOM rating, a fixed capacitor bank was used with a STATCOM. To avoid overexcitation, the maximum reactive power that can be provided by the fixed capacitor bank is the no-load requirement of the wind farm, where the rest is supplied by a STATCOM.

Table 1
The 2.3 MW induction machine parameters (kindly provided by Siemens)

Rating	2.3 MW
Stator voltage (L–L, RMS)	0.69 kV
Number of pair pole	2
Stator resistance	0.006 p.u.
Stator inductance	0.162 p.u.
Mutual inductance	3.65 p.u.
Rotor resistance	0.008 p.u.
Rotor inductance	0.06 p.u.
Combined inertia constant of the generator and the turbine	5.71521 s

The reactive power required by a grid connected induction machine can be calculated in a manner similar to that used to calculate the capacitance required for a self-excited induction generator (SEIG). The capacitance can be calculated either by mesh analysis [9], or by nodal analysis [10,11].

Nodal analysis was used to calculate the no-load and the full-load reactive power requirement of a fixed speed wind turbine based on a 2.3 MW induction generator which was used in the simulations explained in Section 5. The parameters of the 2.3 MW induction machine shown in Table 1 are given referred to the stator winding. The no-load, and the full-load reactive power required for the 2.3 MW induction machine were calculated to be 600 and 1200 kVAr, respectively. These values were verified using the Matlab/Simulink and the Simulink outputs are shown in Fig. 3.

4. System description

In order to study the effect of SCR on the compensator rating of a fixed speed wind farm, and to investigate the compliance of fixed speed wind farm with the new UK grid code, the system shown in Fig. 4 was studied. The network consists of a 60 MW wind farm, two 25 km overhead transmission lines, 132/11 kV (80 MVA) transformer, STATCOM, 11/0.69 kV (80 MVA) transformer and a capacitor bank. The wind farm consists of 26 fixed speed wind turbines, each with its own 0.69/11 kV transformer. Each wind turbine drives a 2.3 MW induction generator, the parameters of which are shown in Table 1. However, in order to simplify the simulation, the whole wind farm was modelled as one lumped machine.

5. System modelling

The induction machine model used in this study is based on a fourth-order state-space model [12]. This model is a built-in model in the simPowerSystem library in Matlab/Simulink. In order to simulate the whole wind farm as one lumped machine all the 0.69/11 kV transformers were represented as one equivalent transformer.

All the parameters of the 2.3 MW induction generator are given in p.u.; hence the lumped induction machine parameters remains the same as those of 2.3 MW machine

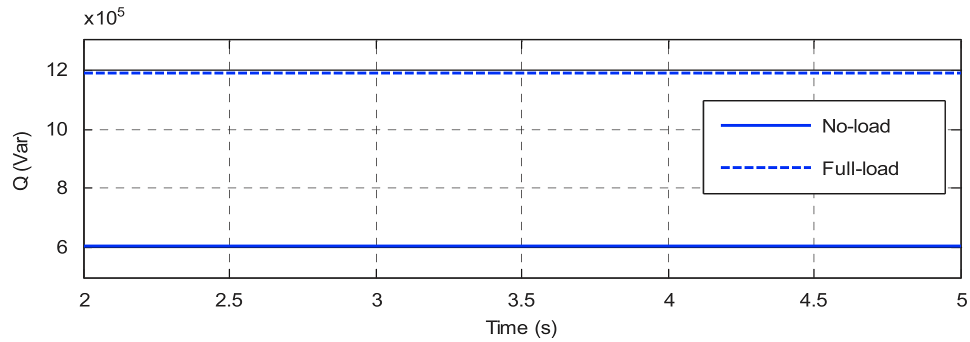

Fig. 3. No-load and the full load requirement of the 2.3 MW induction generator.

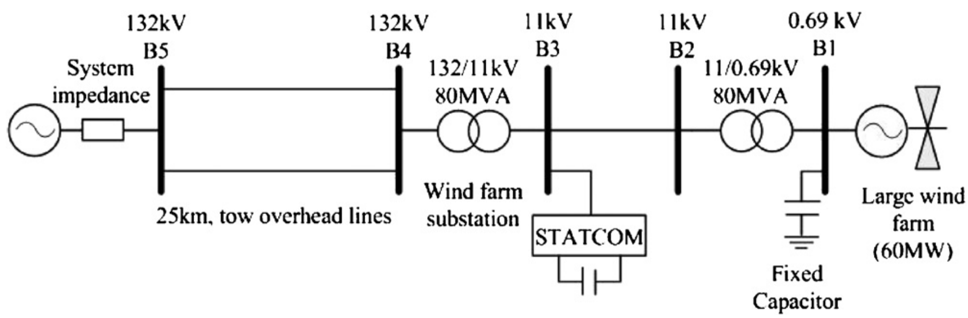

Fig. 4. Network model.

except the MW rating, and the inertia constant. The MW rating was set to 60 MW, and the inertia constant was set according to the following equation [13]:

$$\frac{H_1}{H_2} = \frac{\sqrt{S_1}}{\sqrt{S_2}}, \tag{1}$$

where, H is the inertia constant in seconds and S the wind turbine capacity in MVA

The two 25 km transmission lines connecting buses B5 and B4 shown in Fig. 4 were modelled as PI sections. The line between the buses B3 and B2 in Fig. 4 represents the lines which connect the 0.69/11 kV transformers of each wind generator to the central 11 kV busbar. For the simulations, the parameters of these lines were ignored. This is justifiable as the reactive power which flows in the low voltage cable system is negligible compared with the reactive power which flows in the 132 kV overhead lines. The parameters of the two transformers and the transmission lines are shown in Table 2 and Table 3, respectively.

The built in STATCOM Phasor Model available in the simPowerSystem library under matlab/simulink was used in the simulations. This model is a simplified model similar to the FACTS models found in transient stability software. Despite this simplification it accurately reproduces the dynamic response of a STATCOM in a power system. This model, developed by Hydro-Quebec Power System Simulation Laboratory, is based on the laboratory experience in testing real STATCOMS for various utilities [14].

Table 2
Transformer data

Wind farm side transformer data (0.69/11 kV)	
Rating	80 MVA
$V_{\text{secondary}}$ (L–L, RMS)	0.69 kV
V_{primary} (L–L, RMS)	11 kV
L	0.04 p.u.
Grid side transformer data (11/132 kV)	
Rating	80 MVA
$V_{\text{secondary}}$ (*L–L*, RMS)	11 kV
V_{primary} (*L–L*,RMS)	132 kV
L	0.12 p.u.

Table 3
Transmission line parameters

Resistance	0.17562 Ω/km
Inductance	1.2436 mH/km
Capacitance	9.3169 nF/km

6. Simulation studies

In the simulation studies, the reactive power requirement of the 60 MW wind farm under both steady state and transient conditions, the effect of the SCR on the reactive power requirement, and the compliance with new UK grid code requirements were investigated.

The reactive power required by the 60 MW lumped induction machine was calculated by multiplying the reactive power requirement of the 2.3 MW machine by 26. The no load and full load requirements for the 60 MW lumped model was calculated to be 15 and 30 MVar, respectively.

However, the new UK grid code for wind farms requires the wind farms to be able to supply rated MW output at any point between 0.95 power factor lagging and 0.95 power factor leading at the point of connection with the UK transmission system. This implies that if the 60 MW wind farm operates at 0.95 power factor lead, the compensation devices have to supply about 20 MVar to the grid plus the reactive power required for the wind farm (i.e., the reactive power required by the induction generators, the transmission lines and the set-up transformers). Note that, the reactive losses in the step-up transformer (11/132 kV) are high, because the transformer's impedance is usually high to limit fault currents.

6.1. Reactive power required by the transmission lines and the transformers

The reactive power required by the transformers, the transmission lines and the grid has to be considered in the compensator rating. In order to calculate the reactive power required by the transmission lines and the transformers the network shown in Fig. 4 was simulated under full load condition (i.e., the wind farm is generating at full capacity power). Note that during this simulation the rating of both the STATCOM, and the fixed capacitor bank was 30 MVar, and the SCR at the point of connection was 11 (strong system). Fig. 5 shows that wind farm obtains the reactive power required from the STATCOM, and the fixed capacitor bank, when the transmission system draws about 7.7 MVar from the grid. Therefore the reactive power required by the transmission line and the transformer, when the 60 MW wind farm operates at the rated power is 7.7 MVar.

6.2. Effect of SCR and the grid code on the compensator rating

The total reactive power required for the 60 MW wind farm is approximately 38 MVar; 30 MVar for the wind farm and 8 MVar for the transmission lines and the transformers. In these studies, a fixed capacitor of 15 MVar is used to supply the no load reactive power require by the wind generators, and a STATCOM rated 15 MVar is used to supply the additional reactive power required by the wind generators under full load. An extra 8 MVar of switched capacitor bank is used to supply the reactive power required by the transmission system.

In order to investigate the effect of the strength of the grid on the compensation required for stable operation of the wind farm three cases were considered; where the SCR at the point of connection was set to three, four and five. Both the steady state and the dynamic behaviour of the wind farm were investigated in each case under two conditions; first, when the reactive power required by the wind farm only is considered in the compensator rating (30 MVar) i.e., the 8 MVar switched capacitor bank was not considered, second, when the 8 MVar switched capacitor bank is considered.

In the *first case*, the circuit shown in Fig. 4 was first simulated without considering the 8 MVar switched capacitor bank and with short circuit level at the point of connection (bus 5) of 180 MVA; this means that the SCR is 3, representing a weak grid. Results in Fig. 6 shows that the wind farm can not operate and the wind generators overspeed. This is because the grid to which the wind farm is connected is too weak, and hence can not provide the reactive power required by the transmission lines and the step-up transformer.

When the 8 MVar switched capacitor bank is connected to bus 4, the wind farm operates normally. Fig. 7 shows the speed of the lumped machine, and the voltage, the active power and the reactive power at buses 1 and 5. It can be noted that the wind generators run at the desired speed, which is about 1.0095 p.u., and they draw no reactive power from the grid. The wind farm in this case received its reactive power from the fixed capacitor bank (15 MVar), the switched capacitor bank (8 MVar) and the STATCOM (15 MVar).

A three phase to ground fault was applied at the point of connection to the grid (bus 5) at $t = 20$ s for a duration of 140 ms. As shown in Fig. 8 the voltage at bus 5 recovers to 0.95 p.u. within 7.1 s and the active power recovers to 90% (54 MW) of its pre-fault value within approximately 0.5 s.

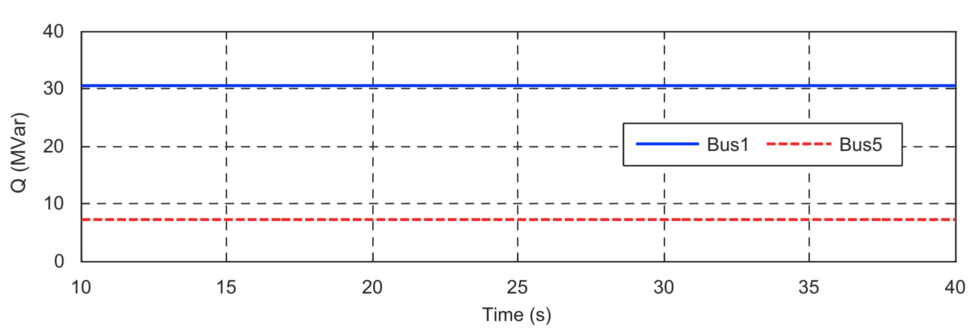

Fig. 5. Reactive power required by the transformers and the transmission lines.

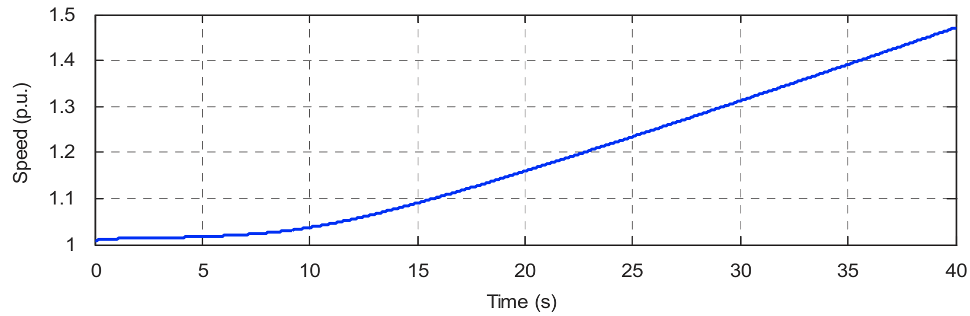

Fig. 6. Speed of the lumped machine in the case of SCR = 3 and the rating of the compensation devices = 30 MVar.

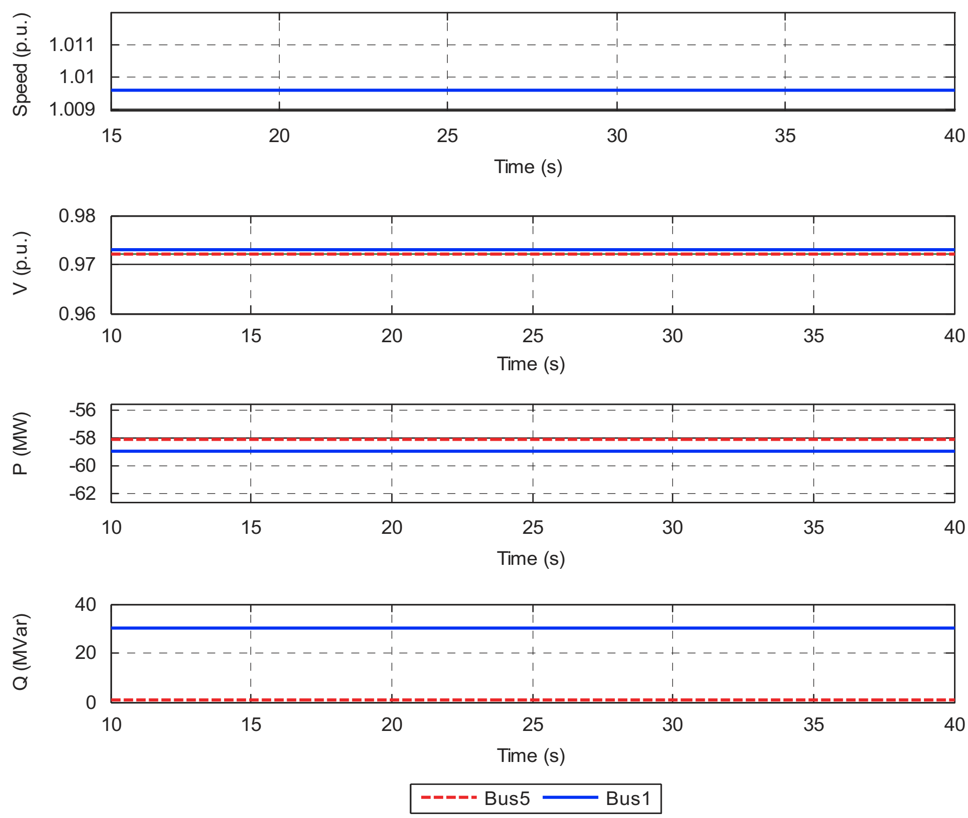

Fig. 7. Speed of the lumped machine and the voltage, the active power and the reactive power at buses 1 and 5 (SCR = 3, compensator rating = 38 MVar).

In the *second case*, the circuit shown in Fig. 4 was simulated with a SCR of 4. When only 30 MVar reactive power capability was considered, the voltage at the point of connection (bus 5) was 0.915 p.u., and at the machine terminals (bus 1) was 0.891 p.u. as shown in Fig. 9, where the speed was slightly higher than the desired speed. In this case the grid cannot provide the reactive power required by the transmission lines and the transformer and the voltage dropped at the point of connection; consequently the speed of the lumped machine was increased. Moreover, if a three line to ground fault is applied at bus 5 at $t = 20$ s for a duration of 140 ms the machine will overspeed as shown in Fig. 10.

However, if a 38 MVar reactive power capability is considered by connecting the additional 8 MVar switched capacitor bank to bus 4, the voltage at the point of connection (bus 5) and at the lumped machine terminals (bus 1) was improved to 0.988 p.u. and 0.992 p.u., respectively, where the speed was reduced to around the desired speed, as seen in Fig. 11. Moreover, when a three phase to ground fault was applied at bus 5 at $t = 20$ s for a duration of 140 ms, the voltage at bus 5 recovers to 0.95 p.u. within 2.06 s, where the active power recovers to 90% (54 MW) of its pre-fault value within approximately 0.45 s (see Fig. 12).

Finally, in the *third case*, the network shown in Fig. 4 was simulated, but with a SCR at the point of connection

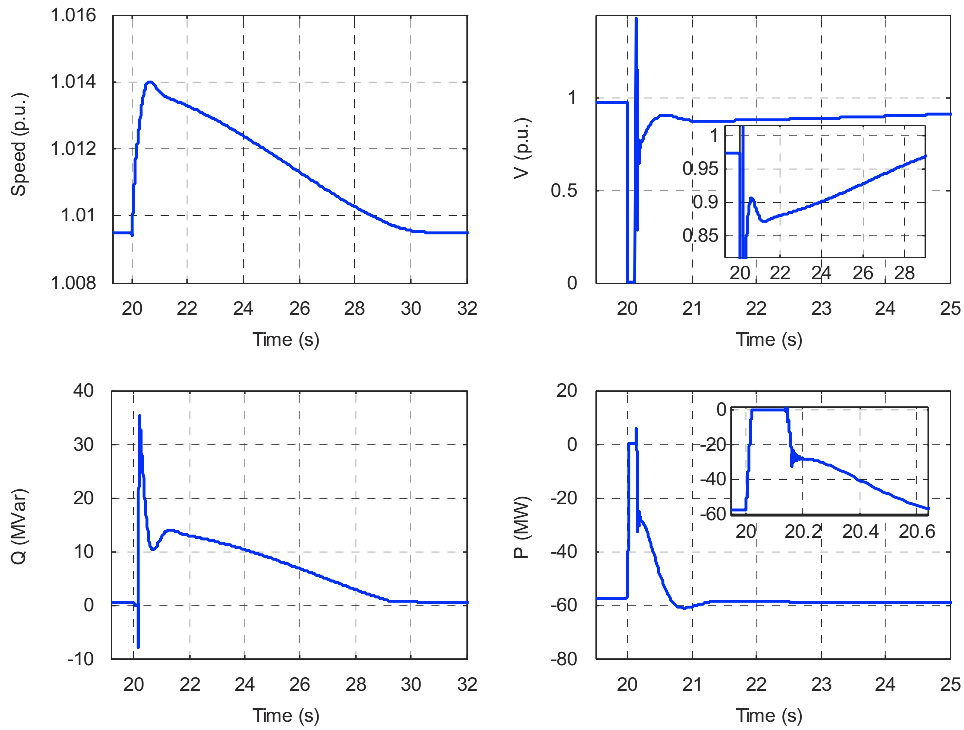

Fig. 8. Voltage, the active power, and the reactive power at bus 5, and the speed of the lumped wind turbine due to fault at bus 5 (SCR = 3, compensator rating = 38 MVar).

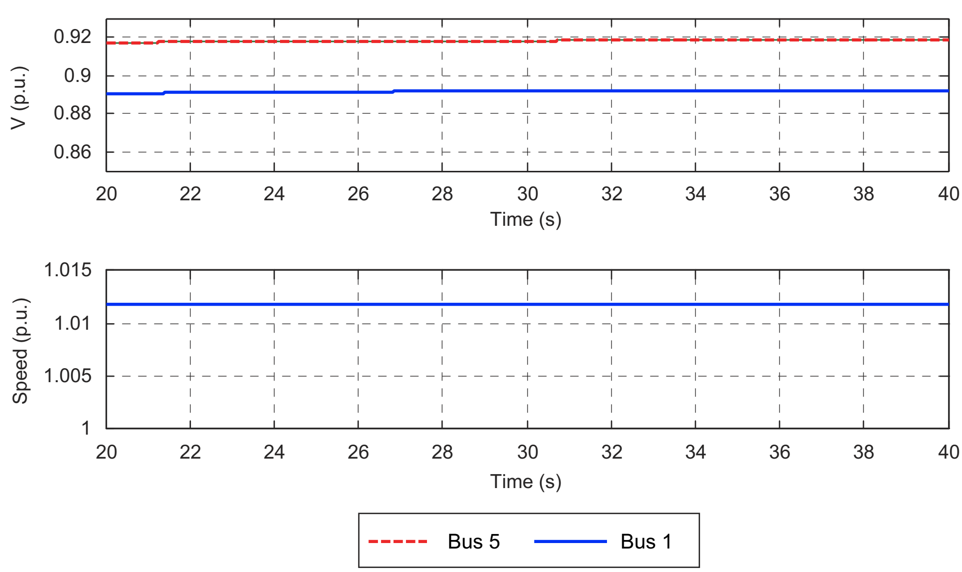

Fig. 9. Voltage profile at buses 1 and 5 and the speed of the lumped machine (SCR = 4, compensator rating = 30 MVar).

of 5. When only 30 MVar reactive power capability was considered, the wind farm draws about 8 MVar from the grid (see Fig. 13). The voltage at buses 5 and 1 was 0.972 p.u. and 0.957 p.u., respectively, and the speed was also slightly higher than the desired speed but lesser than in the second case (i.e., SCR = 4, without the additional 8 MVar capacitor bank) see Figs. 13 and 9. However, with the additional 8 MVar capacitor bank the voltage at buses 5 and 1 was 0.997 p.u. and 1.004 p.u., respectively, and the speed was around the desired speed (see Fig. 14).

For both situations with and without the additional 8 MVar switched capacitor bank, a three phase to ground fault was applied at bus 5 at $t = 20$ s for a duration of 140 ms. The results of both cases are shown in the same graph (see Fig. 15). It can be noted that the voltage, the output active power and the speed of the lumped machine

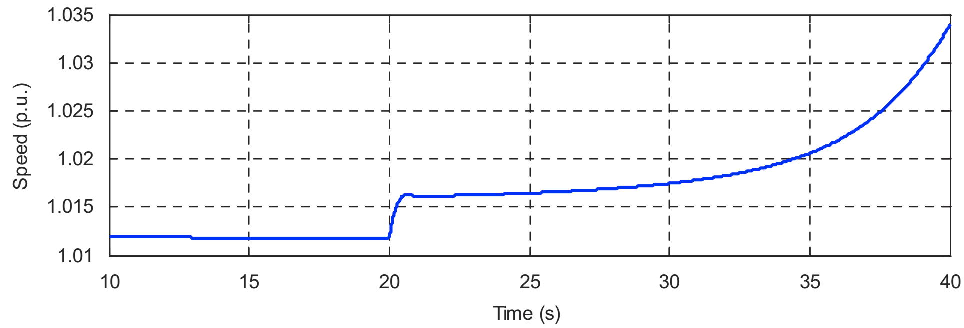

Fig. 10. Speed of the lumped machine in the case of a fault at bus 5 (SCR = 4, compensator rating = 30 MVar).

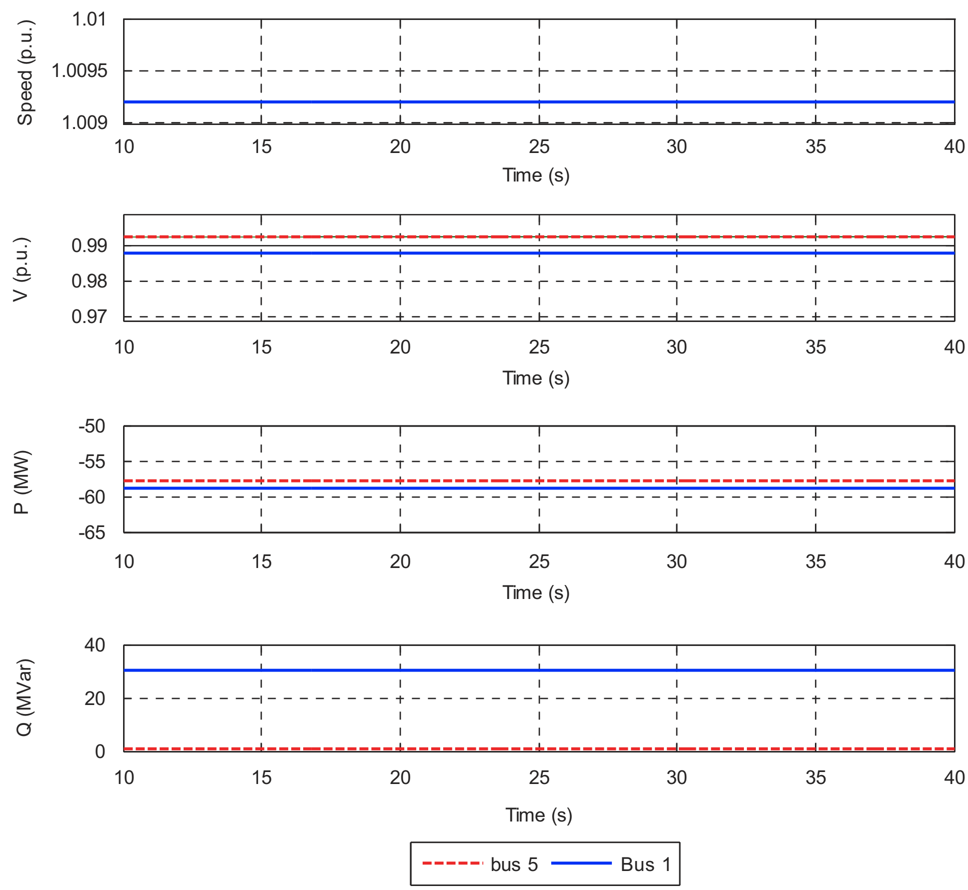

Fig. 11. Speed of the lumped machine and the voltage, the active power and the reactive power at buses 1 and 5 (SCR = 4, compensator rating = 38 MVar).

recover to their rated value faster in the case of the system operates with the additional 8 MVar switched capacitor bank.

Fig. 16 shows a expanded view of the voltage and the output power at the point of connection (bus 5) for both with, and without the 8 MVar switched capacitor bank (SCR = 5). It can be noted that the voltage at the point of connection recovers to 0.95 p.u. within 3.06 s and the output active power at the point of connection recovers to 90% (54 MW) from its pre-fault value within 0.38 s when the 8 MVar switched capacitor bank is not connected. However, if the additional 8 MVar switched capacitor bank is connected, the voltage recovers to 0.95 p.u. within 0.31 s, where the output power recover to 90% of its pre-fault value within 0.35 s.

Fig. 17 shows the relationship between the SCR and the compensator rating as a fraction of the wind farm rating. This graph was obtained by a series of simulations on the network shown in Fig. 4. It can be concluded that the total reactive power required by the wind farm is about

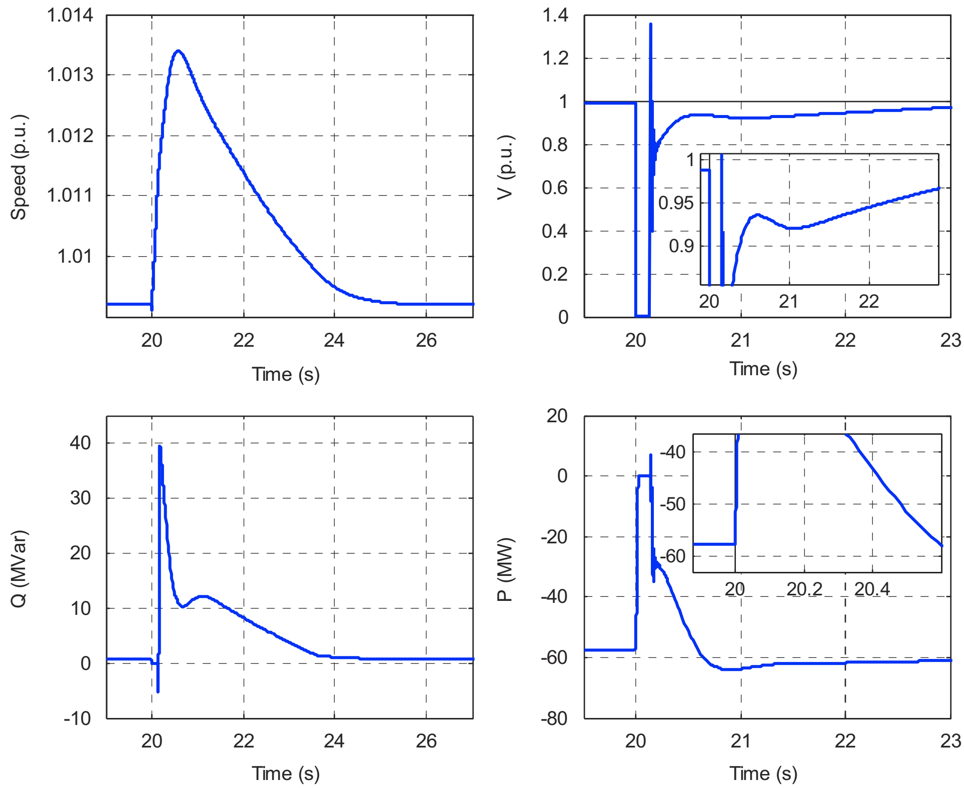

Fig. 12. Voltage, the active power, and the reactive power at bus 5, and the speed of the lumped wind turbine due to fault at bus 5 (SCR = 4, compensator rating = 38 MVar).

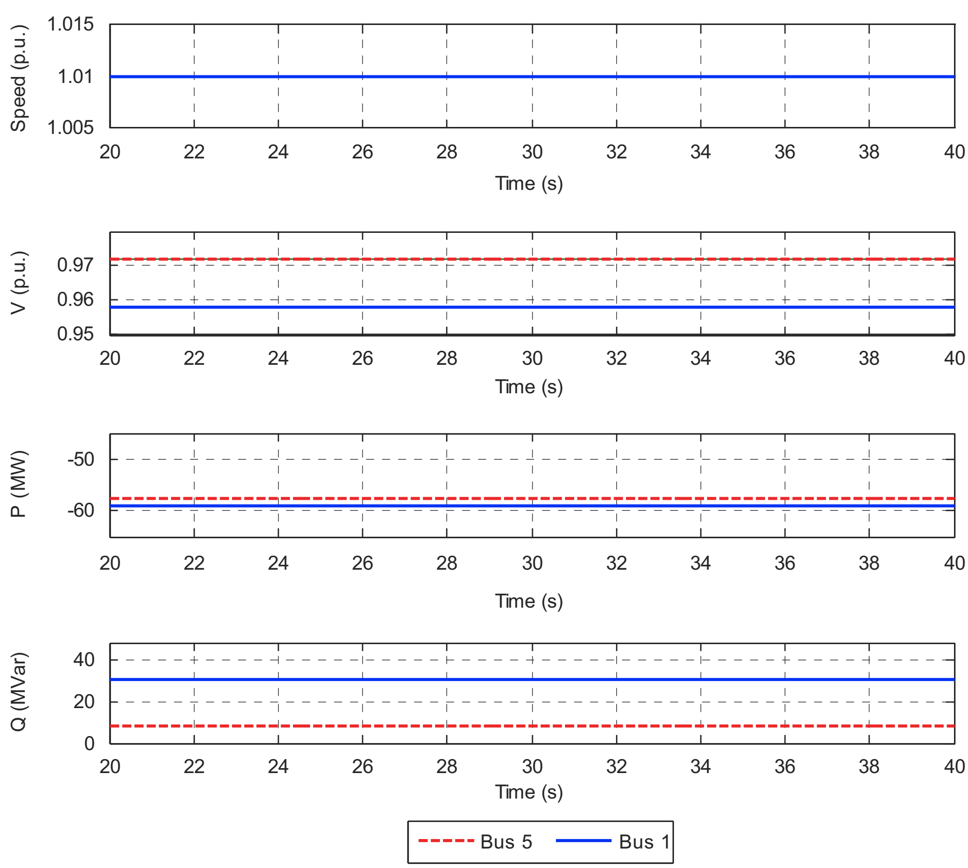

Fig. 13. Speed of the lumped machine and the voltage, the active power, and the reactive power at buses 1 and 5 (SCR = 5, compensator rating = 30 MVar).

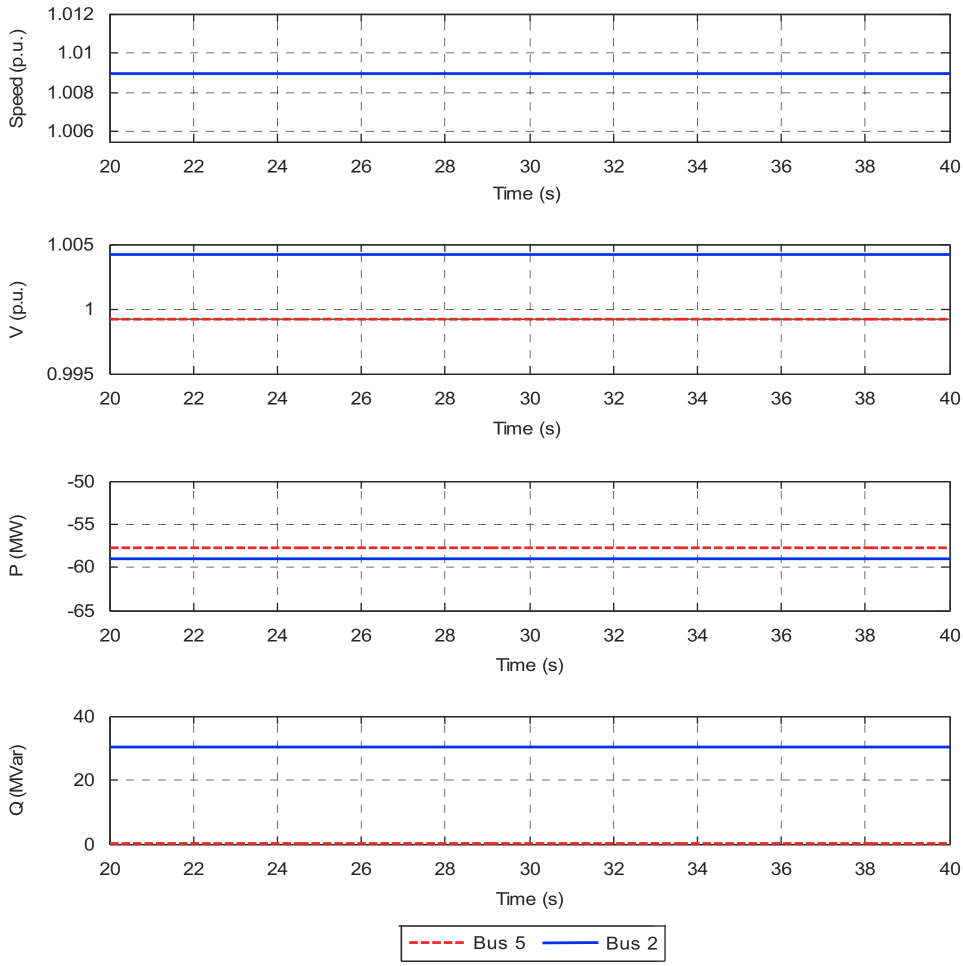

Fig. 14. Speed of the lumped machine and the voltage, the active power, and the reactive power at buses 1 and 5 (SCR = 5, compensator rating = 38 MVar).

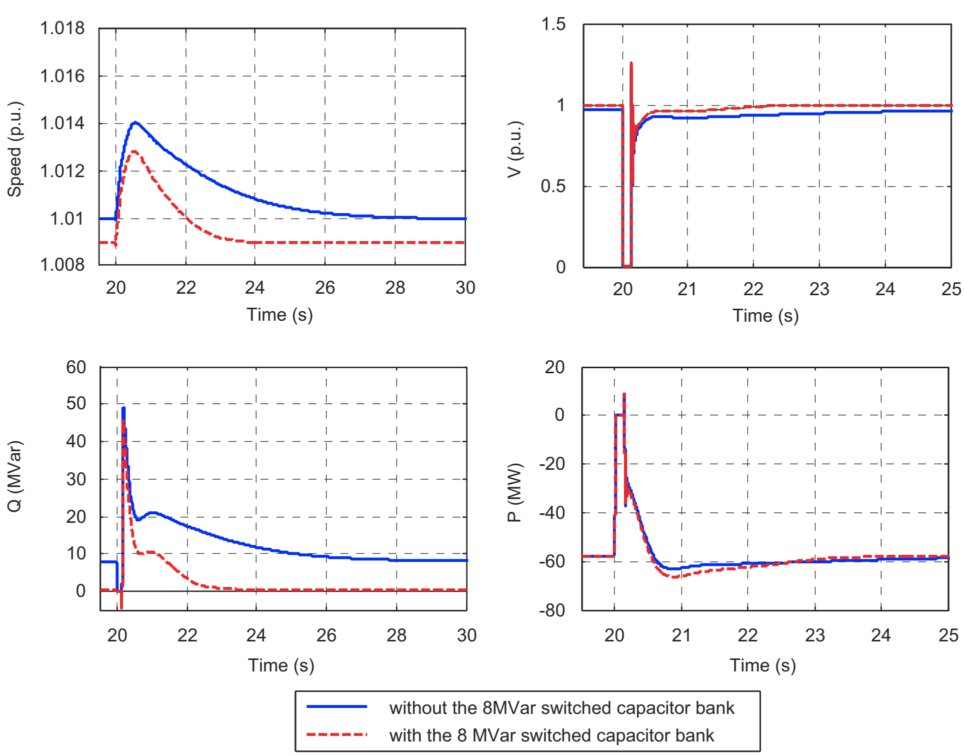

Fig. 15. Voltage, the active power, and the reactive power at bus 5, and the speed of the lumped wind turbine due to fault at bus 5 (SCR = 5).

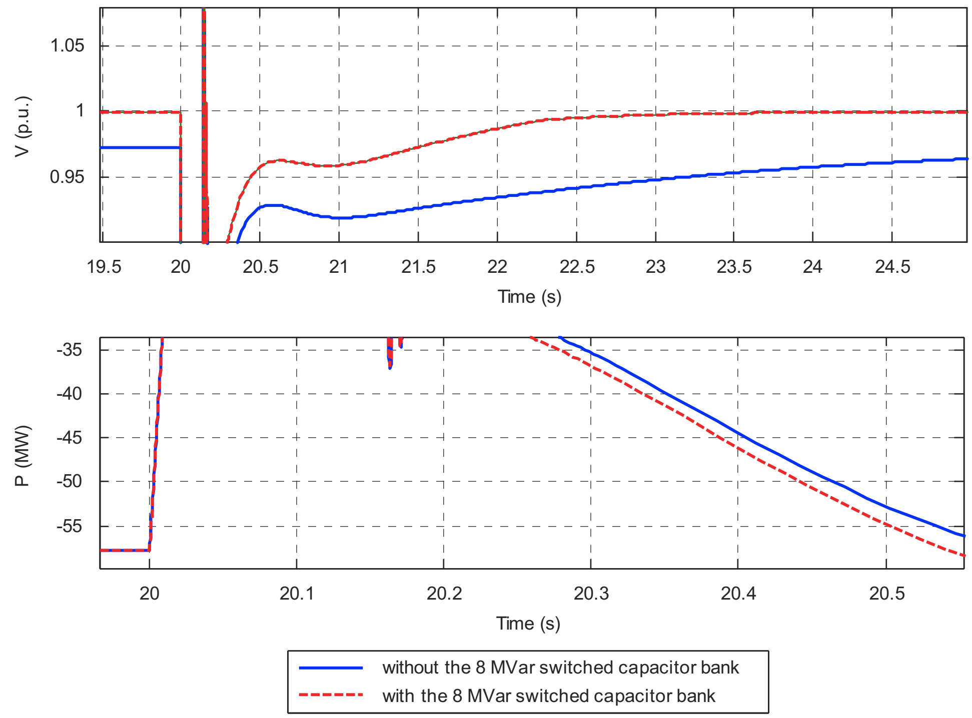

Fig. 16. A zoom in on the voltage and the output power at bus 5 in both cases with and without the 8 MVar switched capacitor bank in the case of a fault (SCR = 5).

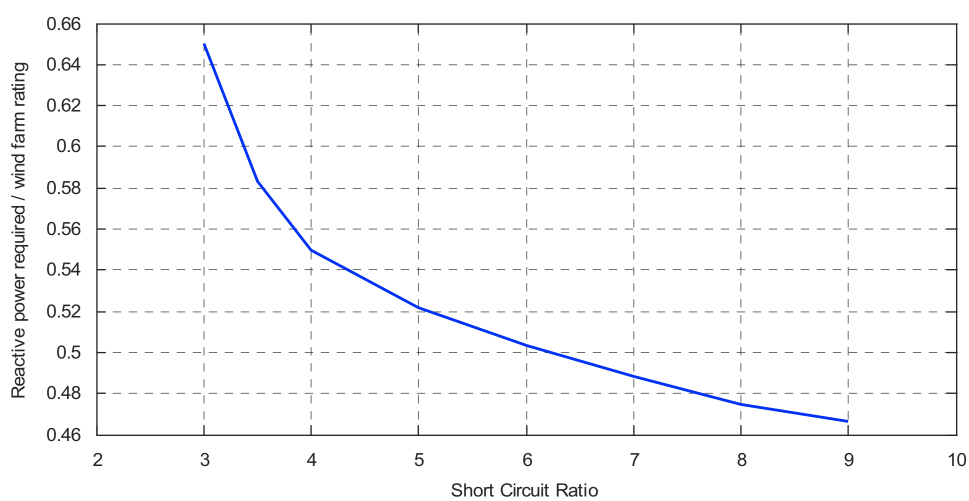

Fig. 17. Relation between the SCR and the compensator rating as a percentage of the wind farm rating.

38 MVar. However, if the wind farm is connected to a strong system (i.e., the SCR = 7 or more), the grid can supply the reactive power required by the transformer, and the transmission line. But with the new grid code requirement which implies that the wind farm may be operated at any point between 0.95 power factor lead or lag at the point of connection with the grid, the 60 MW wind farm has to be able to generate or absorb 20 MVar excess reactive power. This implies that the rating of compensator has to increase.

7. Conclusions

The suitability of fixed speed wind turbines for large wind farms and it compatibility with the new UK grid code was investigated. It was found that, if a fixed speed wind farm was equipped with a suitable compensator it can satisfy the new grid code. However, the compensator rating is very important, and does not depend only on the steady-state requirement of the wind turbines but also the transmission line and the transformer that connect the turbines to the grid. Actually it depends on the grid code requirements.

The new UK grid code states that wind farms have to be able to operate at any point between 0.95 power factor lead or lag at the point of connection with the grid. The effect of this restriction on our case study is to increase the compensator rating by ± 20 MVar. That implies that the compensator has to be able to supply not only the reactive power required by the whole wind farm, including the wind turbines, the transformers and the transmission lines but also has to be able to supply or absorb excess 20 MVar to the grid. This means that the total compensator rating for a 60 MW fixed speed wind farm will be 58 MVar, which can be very expensive comparing to the new variable speed wind turbines which have the inbuilt capability of reactive power control

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