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Fault Ride-through of Wind Parks with Induction Generators

Thesis for the Degree of Master of Science

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Summary

This project deals with the design of the collector system for large wind parks and the study of reactive power compensation techniques to help the wind park meet grid code requirements, especially concerning fault ride-through. In this study, the wind turbine generators are selected to be fixed-speed induction generators without reactive power controllability. The studied wind park is made of one hundred and thirty 3MW wind turbine generators connected to a 20 kV collector system. This collector system is then connected to a 400 kV on-shore transmission grid through two 130 kV cables and transformers.

In the first part of the project, the main design of the collector system was performed by first studying the system load flows using PowerWorld Simulator. From the results of load flows study, ratings and dimensionings of system components are then selected. Reactive power production and consumption of components are calculated and reactive power compensation has been applied in such a way that in steady-state, the reactive power exchange between the wind park and the transmission grid is kept as close to zero as possible.

The second part of the project focuses on simulations of the wind park in PSCAD/EMTDC to study dynamic behavior of the wind park during disturbances (i.e., severe faults) in the connected grid. A study of the fault ride-through capability (FRT) of an induction generator has been conducted using the torque-speed curve approach. The influences of different parameters such as rotor inertia constant, short circuit ratio, and pre-fault operating point on the FRT have been investigated.

Two aggregation methods for large wind farms have been studied and an error estimation has been made. It is shown that a two-machine model is the smallest one that gives an acceptable error in reactive-power flow. A single-machine model is not appropriate to assess fault-ride-through.

FTR and grid code compliance of the wind park with and without additional reactive power support have been compared. The reactive power sources considered are: normal switched shunt capacitors (CAP), static var compensator (SVC), and static synchronous compensator (STATCOM).

The simulation results have shown that either CAP, or SVC, or STATCOM would be a possible solution for the wind park meeting the Nordel grid code requirements on FTR. The needed reactive power support for the wind part is calculated to be 1.6 pu (on a 455 MVA base) for all supporting devices if they are installed at the 130 kV bus closest to the grid. If installed at the main 20 kV bus, the needed sizes could be reduced by 21% and by 38% for CAP/SVC and STATCOM, respectively. If the zero-voltage fault ride-through is not required, the needed size could be reduced significantly. In this case, the required reactive power support from CAP/SVC and STATCOM are found to be 1.00 pu and 0.56 pu, respectively to ride through 0.25 pu voltage dip for 250 ms.

Key words: collector system, wind park, induction generator, fault ride-through, grid code compliance.

Acknowledgements

Contents

Part 0: Background

Recent decades have seen rapid development of wind energy. The size of wind parks is getting larger and larger which leads to emerging problems of design and integration of wind parks into the power system, especially with collector system design, reactive power compensation, and low voltage ride-through capability. In general, the behavior of a wind park strongly depends on many factors, such as: type of wind turbine generator, collector system topology, characteristics of the system to which the wind park is connected, etc. Some knowledge from a literature survey, which is an important background for this study, is presented in this part.

1   Wind turbine generator

There are many concepts of wind turbine generator but they can be divided into three main types: Fixed-Speed, Variable-Speed with Full Converter, and Variable-Speed with Doubly-Fed Induction Generator [1].

1.1   Fixed-Speed Wind Turbine

In this scheme, the induction generator is directly connected to the grid as in Figure 1.
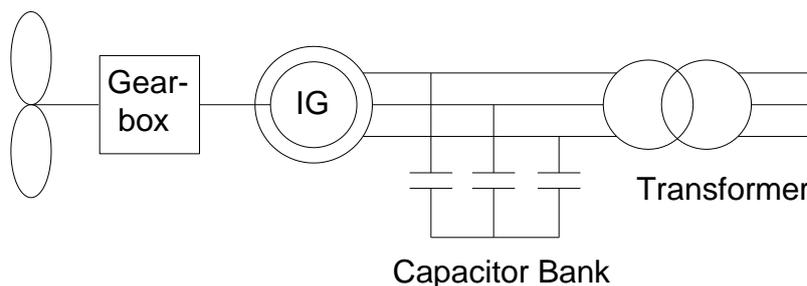
Figure 1 Fixed-Speed Wind Turbine [1]

The role of the gear box is to transmit low-speed motion of the turbine to higher-speed of the generator rotor. The transformer is employed to step up the voltage from standard generator level to the level of the collector system. In this scheme, capacitor banks are usually installed at the terminal of the induction generator to compensate for the reactive power consumption of the magnetizing branch. The speed of the generator is determined by the system frequency and the number of pole pairs. This is the simplest and cheapest scheme but it gives some limited performances which can be found in hundreds of papers in the literature. One of the most concerned points in this study is that this scheme has no capability of reactive power or power factor control which means it requires controllable reactive power sources in the system.

1.2   Variable-Speed Wind Turbine with Full Converter

The generator is connected to the grid via a power electronic converter as in Figure 2.
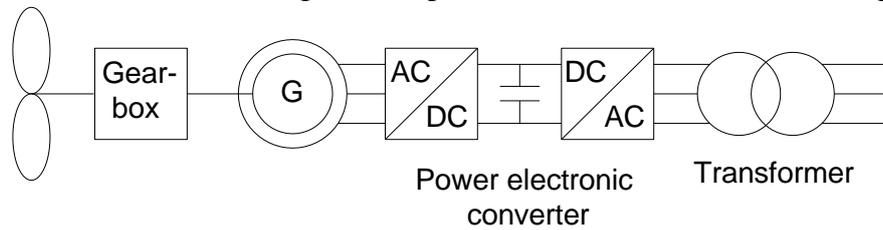
Figure 2 Variable-Speed Wind Turbine with Full Converter [1]

The converter is connected to the stator of the generator; this converter has to be able to convert full power from the generator. The generator in this scheme could be either an induction generator or a synchronous generator. The gear box can be removed or simplified if a synchronous generator with multiple poles is employed. This scheme has very flexible capability of reactive power control.

1.3   Variable-Speed Wind Turbine with Doubly-Fed Induction Generator

This scheme also employs a power electronic converter as in Figure 3. The main difference is that this converter is connected to the generator rotor; the stator is directly connected to the grid.
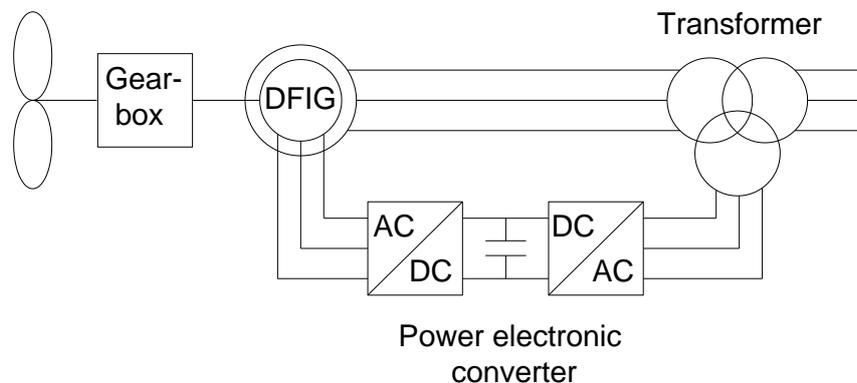
Figure 3 Variable-Speed Wind Turbine with Doubly-Fed Induction Generator [1]

Compared to the one with full converter, this scheme is more suitable for high power wind turbines since only a fraction (typically 20-30%) of the total power goes through the converter. This gives possibility to design the converter with smaller size, and as a result, lower cost and lower power electronic losses.

2 Collector System Topology

The design of the collector system is normally based on the turbine arrangement designed to maximize the captured power from the wind and to avoid turbulence effects between turbines [e.g.2]. Thus, collector system topology must fit with this arrangement. In addition, this topology is also decided by other factors such as the availability of cables, reliability, costs. Some examples of collector system connection are shown in Figure 4. More detailed discussions on these topologies can be found in [2].
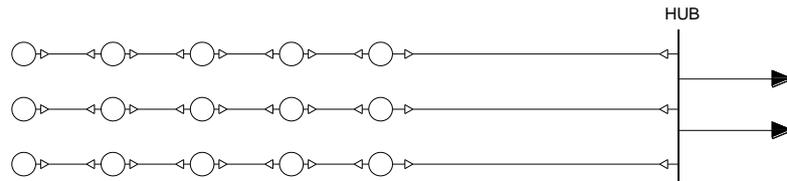
"Radial" clustered wind turbine connected to single hub
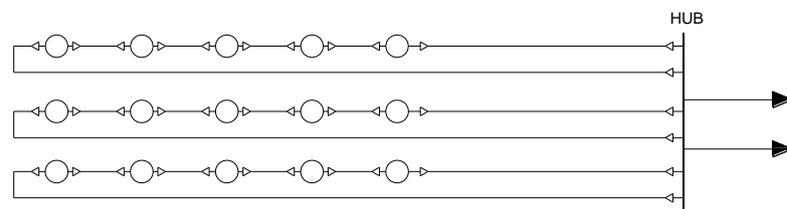
"Single sided ring" clustered wind turbine connected to single hub
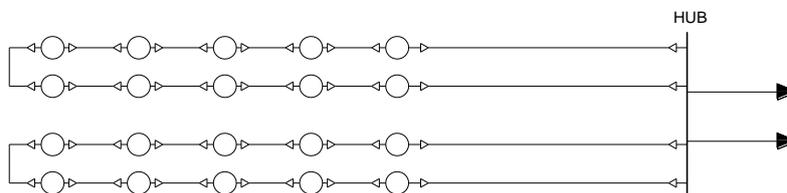
"Double sided ring" clustered wind turbine connected to single hub
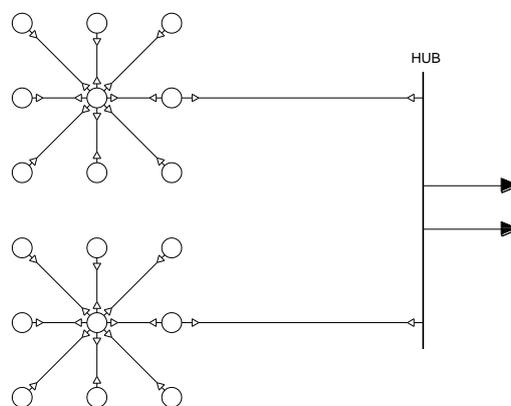
"Star" clustered wind turbine connected to single hub

Figure 4 Examples of collector system connection

3 Ride-through capability and Grid Code compliance

Due to the increase of wind energy penetration into the system, the Transmission System Operators (TSOs) put some strict requirements on the wind parks, including reactive power control and ride-through capability.

According to the Nordel Grid Code [3], the wind park must have adequate reactive power to be able to operate at zero reactive power exchange at the point of connection. It also requires that the wind park must be able to automatically control its reactive power exchange as a function of voltage at the point of connection with the purpose of controlling the voltage.

Nordel Grid Code also puts a very strict requirement for the wind park to be able to stay connected during and after system disturbances. This requirement is presented by a voltage dip profile curve in Figure 5.
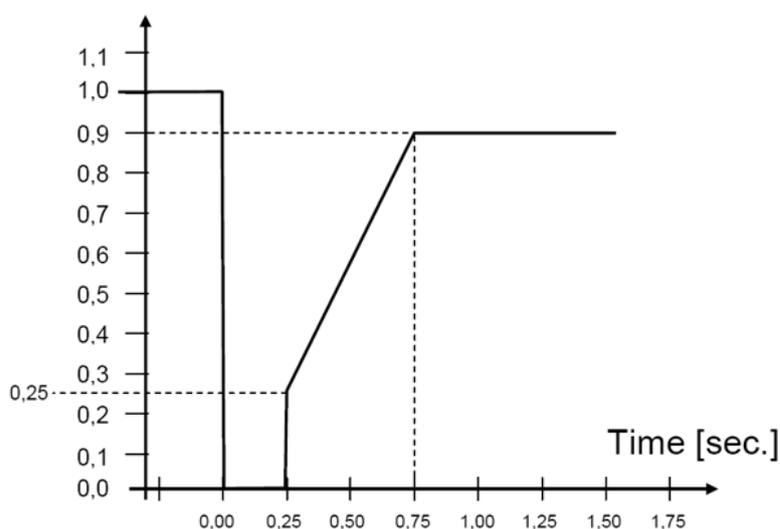
Figure 5 Voltage dip profile, Nordel Grid Code

According to this curve, the wind park has to be able to ride through any system disturbances which make the voltage at the high voltage connection point fall in the area above the curve. From this requirement, the wind park has to withstand zero voltage for 250 ms. This strict requirement may require the employment of reactive power supporting devices in the system.

4 Reactive power compensation techniques

For a wind park with induction generators, the main requirements for compensation devices are to compensate for any reactive power demand of the induction generators in steady state to control reactive power exchange with the system, and to help the recovery of wind parks after system disturbances to improve ride-through capability. The former can be fulfilled by a simple solution with conventional switched shunt capacitors while the latter requires dynamic compensation devices with more advanced control algorithms.

Recent technology gives three solutions for dynamic reactive power compensations. They are based on different control algorithms for three shunt compensation devices: Switched Shunt Capacitor/Reactor, Static Var Compensator (SVC), and Static Synchronous Compensator (STATCOM).

Switched shunt capacitor can be switched either by mechanical or Thyristor based switches. An SVC is a combination of Thyristor Switched Capacitors (TSCs) and a Thyristor Controlled Reactor (TCR) as in Figure 6 [4].
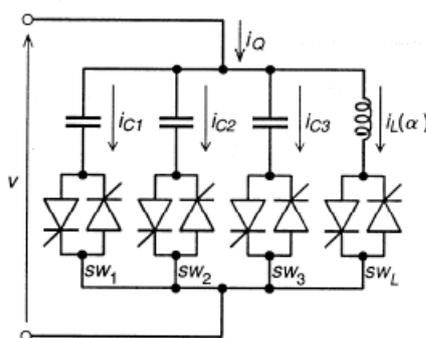
Figure 6 SVC [4]

Switched shunt capacitor/reactor and SVC operate on the same principle; they are both based on the reactive power production or consumption of capacitive or inductive impedance. Thus, their current is proportional to terminal voltage and the reactive power is proportional to square of voltage as in Figure 7.
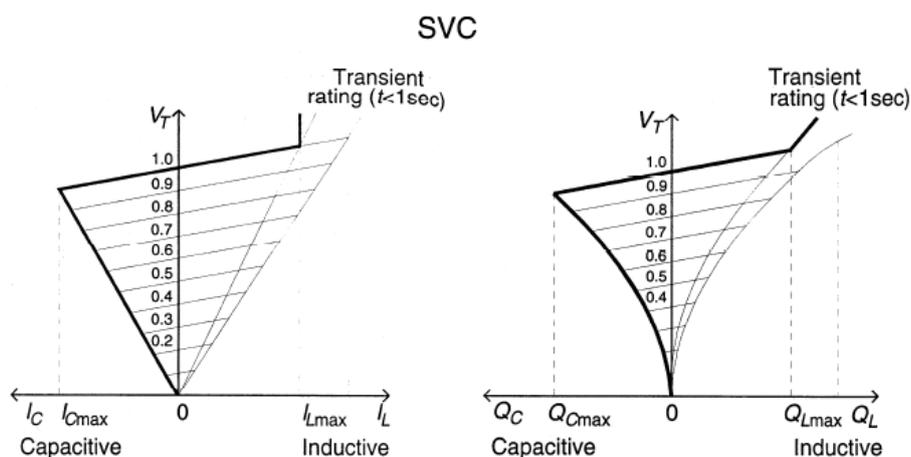
Figure 7 V-I and V-Q characteristics of SVC [4]

The main difference between switched shunt capacitor and SVC is that SVC is able to control reactive power or voltage smoothly by combinations of different TSCs and firing angles of TCR. Better performance of a switched shunt capacitor bank can be obtained by splitting it into smaller banks and using a suitable control scheme.

Apart from the two devices above, the principle of a STATCOM is based on a power electronic converter based voltage source as in Figure 8. The basic principle of a voltage source behind a reactance is the same as for the synchronous condenser. However a STATCOM provides faster and more flexible control.
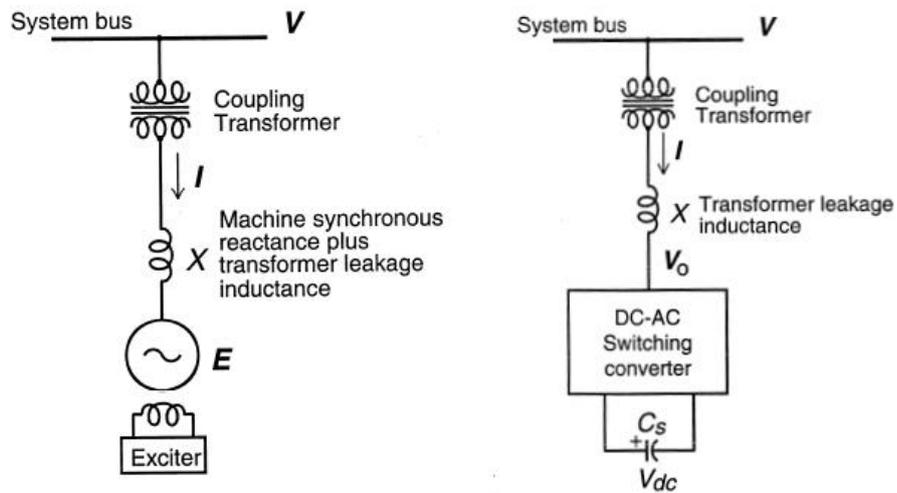
Figure 8 Condenser and STATCOM [4]

Based on the voltage source, the current or reactive power output from a STATCOM is controlled by the voltage difference over the inductance. Thus, its current can be kept constant and reactive power is proportion to the voltage as in Figure 9.
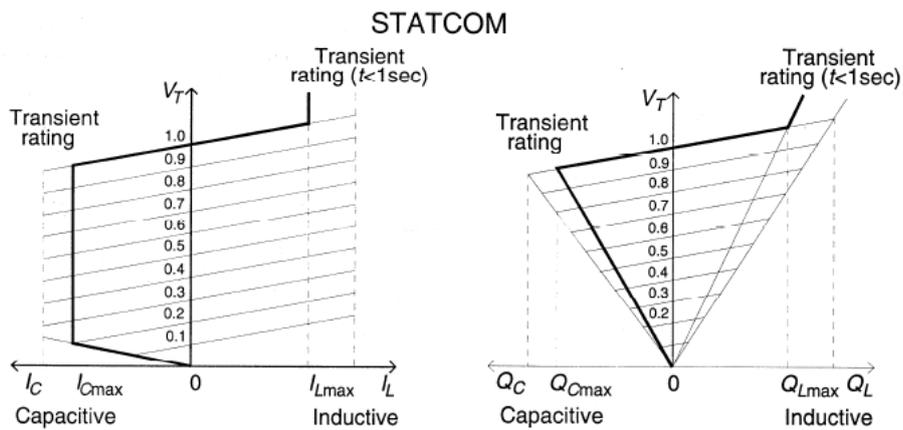
Figure 9 V-I and V-Q characteristics of STATCOM [4]

Detailed discussions on the characteristics and applications of these devices can be found in [4]. Any of these devices or combination of them could be a solution to reactive power compensation for wind parks.

Part 1: Design of Wind Park

1 Introduction

The aim of this part of the project is to design a 390 MW offshore wind park located 50 km from a 400 kV substation which is considered as the "point of connection" (PoC). The tasks include configuration and selection of components in the system such as: cables, transformers, and shunt devices.

A power flow calculation software (PowerWorld Simulator) is used to observe the behavior of each component as well as the whole system in different operation conditions in steady state.

Reactive power compensation is also taken into consideration in this part. Since all wind turbine generators are induction machines in this case, there is a big demand of reactive power at full generation. In the first stage, this demand should be compensated by shunt capacitors. The size and location of these shunt capacitors are also considered in this part.

2 Wind park configuration

2.1   Selection of turbine generator units

As mentioned earlier, total capacity of the wind park is 390 MW. One hundred and thirty 3 MW (3.5 MVA) wind turbine generators (WTGs) are used. Each unit includes a 3MW wind turbine with an induction generator and a 3.5 MVA step-up transformer. The step-up transformer is used to step up the voltage from the standard level of WTGs at 690 V to the level of collector system at 20 kV. The voltage level of 20 kV is chosen according to the capacity of the wind park and availability of cables.
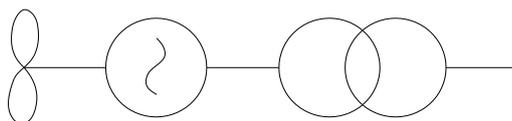
Figure 10 Wind turbine generator unit

2.2   System configuration

According to availability of cable, configuration for a group of WTGs (a feeder) is decided; each feeder includes 10 WTGs. The distance between the WTGs is 0.8 km and the distance from the nearest WTG to the 20kV collector hub is 2 km. The WTGs are connected by 20 kV cables as shown in Figure 11.

The number of WTGs in one feeder is selected according to the availability of cables which will be mentioned later in Section 2.3. Configuration for the whole system is presented in Figure 12.
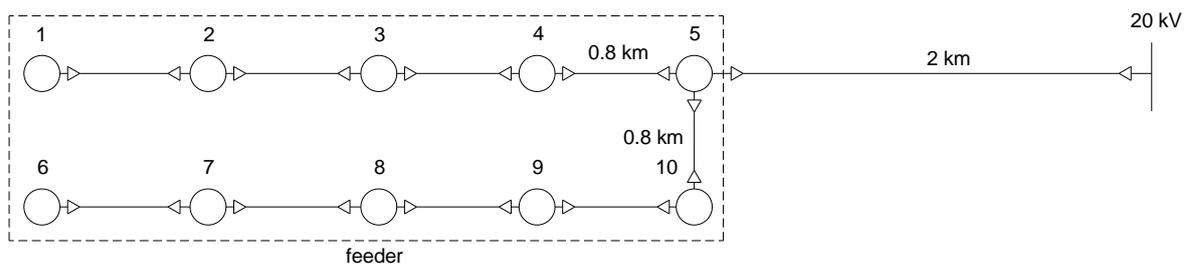
Figure 11   Configuration of one feeder
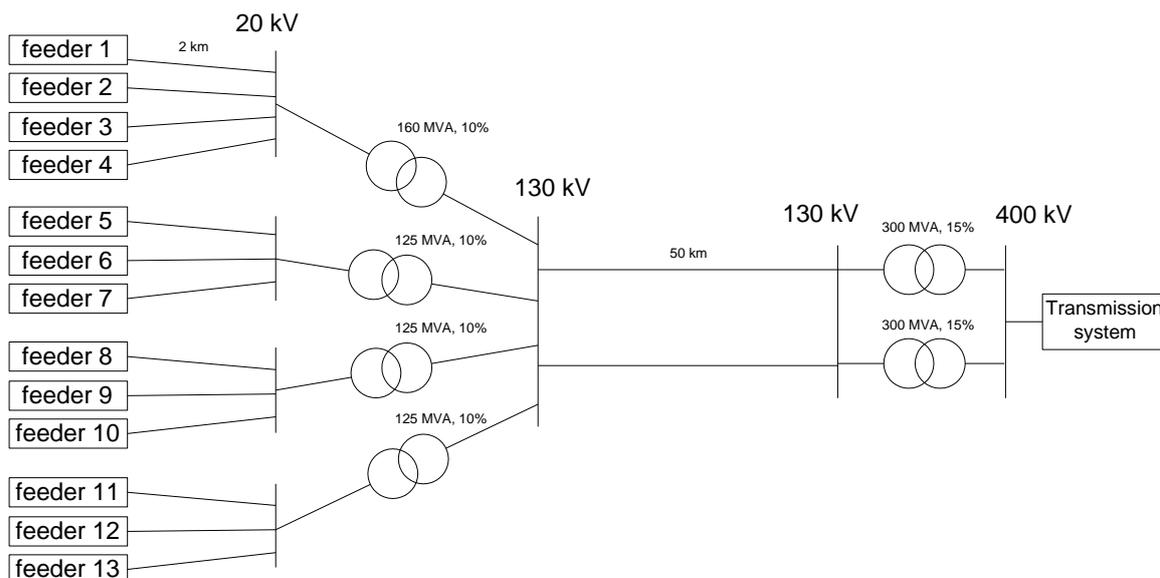
Figure 12   Configuration of the system

The whole system includes 13 feeders. According to availability of standard rating of transformers, four feeders are connected in group 1 and each of 3 other groups is made of 3 feeders. Each group is connected to a transformer to step up the voltage to 130 kV. The wind park power is transmitted to the 400 kV transmission system through two 50 km interconnection cables and two step-up transformers as in the figure. Details of component selection are discussed in the next section.

2.3   System component selection

In order to select the system components, reactive power consumption of WTGs must be known. The following section describes a method to estimate reactive power consumption of induction machines which are used for the WTGs in this project.

2.3.1   Reactive power consumption of WTGs

As previously mentioned, induction generator is chosen for all WTGs. According to [5], there is a relatively large demand of reactive power from the WTGs. The study says that usually capacitors are installed at the terminals of WTGs to compensate for the reactive power consumption of the magnetizing branch of the induction generator. Thus, on the

high voltage (HV) side of the generator transformer, the maximum reactive power consumption is equal to:

$Q = P^2 X_l + P^2 X_t = P^2(X_l + X_t)$, all parameters are in per-unit

where,

P: rated active power of WTG, which is 3 MW

X_l: leakage inductance of induction generator

X_t: reactance of 0.69/20 kV transformer

The leakage inductance of the induction generator, X_l, is around 0.2 pu and reactance of transformer, Xt, on 3 MVA base of 0.1 pu is chosen. Using this data, maximum reactive power consumption of one WTG is determined:

Q = 1^2*(0.2+0.1) = 0.3 pu

Q = 0.3*3 = 0.9 MVAr

2.3.2 Selection of collection cable

According to the availability of cable in [6], one feeder of 10 WTGs is decided. Each feeder has maximum generation of 30 MW and 9 MVAr reactive power consumption by ten WTGs. The voltage level of the collector system is 20 kV, the maximum current is:

$$I = \frac{\sqrt{P^2 + Q^2}}{\sqrt{3}*U} = \frac{\sqrt{30^2 + 9^2}}{\sqrt{3}*20} = 904 \text{ A}$$

In order to ensure redundancy, one additional cable segment is used to connect node 1 and node 6 in Figure 11. With this configuration and by selecting the same size for all cable segments, it enables backup supply in case of a failure of any cable segments between wind turbines.

The cable selected is XLPE, single core, copper conductor with parameters in Table 1.

Table 1 20 kV cable parameters [6]

Cross section mm^2	Diameter Mm	Current capability A	R(DC at 20°C) Ω/km	C μF/km	L mH/km
800	33.7	1070	0.0221	0.52	0.50

2.3.3 Selection of transformers

There are two types of transformer in the system: one is the sub-transmission transformer to step up the voltage from 20 kV to 130 kV and one is the transmission transformer to step up the voltage from 130 kV to transmission voltage level at 400 kV.

For the sub-transmission transformer, there is only one transformer for every feeder. Their capacity should be chosen in such a way that they are able to transfer the maximum power from the WTGs in the group. According to this requirement, together with standard ratings

of power transformer, the parameters of sub-transmission transformers are given in Table 2.

Table 2   Selection of sub-transmission transformers

Group	Maximum active power (MW)	Maximum reactive power (MVAr)	Maximum apparent power (MVA)	Capacity of transformers (MVA)	Rated voltage (kV)	$\varepsilon_n\%$ (%)
1	120	36	125.28	160	20/132	10
2	90	27	93.96	125	20/132	10
3	90	27	93.96	125	20/132	10
4	90	27	93.96	125	20/132	10

For the transmission transformers, in order to increase reliability, two transformers working in parallel are selected. The capacity of transformer should be chosen in such a way that when one is out of service, the remaining must be able to transfer the maximum power with its overload capacity of 40% for certain duration.

According to the design, maximum active power generation of the wind park is 390 MW, and to fulfill the grid code requirements, reactive power exchange between the wind park and the system in normal operating condition is expected to be as close to zero as possible. Thus, capacity of these transformers is selected as following:

$$S_{capacity} \geq \frac{390}{1.4} = 278.57 MVA$$

A capacity of 300 MVA is chosen in order to ensure a safety margin in case that reactive power exchange is needed. The parameters of these transformation transformers are given in Table 3.

Table 3   Parameters of transmission transformers

Capacity (MVA)	Rated voltage (kV)	$\varepsilon_n\%$ (%)
300	132/400	15

2.3.4 Selection of interconnection

Recent studies show that there are three possible solutions for interconnection lines; they are: High Voltage Direction Current (HVDC) cable, High Voltage Alternative Current (HVAC) cable, and HVAC overhead line.

The distance from the wind park to the point of connection is assumed to be 50 km. According to [7], HVAC takes advantages over HVDC for short transmission distance in terms of investment costs. In addition, it is impossible to have overhead line offshore. Thus, HVAC cable is selected for this study.

Two-parallel-cable solution is selected due to the reliability and relatively high transferred power. As previously mentioned, reactive power exchange at the point of connection is

expected to be zero in normal operating condition. The cable thus must at least be able to transfer the maximum active power from the wind park and reactive power consumed by the transmission transformer.

Assume that there is no downstream reactive power load; reactive power consumption of two transmission transformers can be calculated as follows:

$$Q_{consumption} = 2*3I^2.X = 6\left(\frac{P}{2\sqrt{3}U}\right)^2 * \varepsilon_n\% * \frac{U^2}{S_{capacity}} = \frac{P^2}{2S_{capacity}} * \varepsilon_n\%$$

where,

I: current flowing through one transformer

X: transformer impedance

$\varepsilon_n\%$: transformer short circuit voltage, 15%

P: maximum transferred power; assume to be equal to wind park power, 390 MW

$S_{capacity}$: capacity of transformer, 300 MVA

Inserting values gives solution: $Q_{consumption}$ = 38.025 MVAr

Ignore active power loss, current flow through the transmission cable can be calculated:

$$I = \frac{\sqrt{P^2 + Q_{consumption}^2}}{2\sqrt{3}*U} = \frac{\sqrt{390^2 + 38.025^2}}{2\sqrt{3}*130} = 870.13 \text{ A}$$

According to [6], 132 kV, single core, copper conductor, XLPE cable is chosen with the parameters given in Table 4.

Table 4   130 kV cable parameters [6]

Cross section (mm^2)	Diameter (mm)	Current capability (A)	R(DC at 20°C) (Ω/km)	C (μF/km)	L (mH/km)
1000	37.9	960	0.0176	0.25	0.35

3 Reactive power compensation

3.1   General concept

Reactive power compensation is of great interest when designing wind parks. Most of transmission system operators require zero or very small reactive power exchange at the point of connection. In addition, wind parks must be able to control their reactive power exchange as required in order to control the voltage and to help improve stability of the system in emergency conditions.

Available reactive power compensation techniques were previously mentioned in the Background part. These techniques are studied and applied to the system to fulfill the requirements both in steady and transient states.

In the first stage of this project, the size of compensation devices is chosen with two targets:

- Exchange of reactive power at point of common connection in normal operation is as close to zero as possible.
- Voltage levels in normal operation at all buses in the system are kept in the range of 0.95 to 1.05 pu.

Further consideration with reactive power compensation, especially with SVC or STATCOM, is studied in the second stage of this project when the system is simulated with PSCAD/EMTDC to analyze its dynamic behavior during system disturbances.

3.2 Reactive power production and consumption in the system

Assume that all components operate in rating condition, reactive power production and consumption in the system can be roughly estimated:

From two 130 kV cables:

$$Q_{130kVCables-production} = 2\frac{U^2}{X_C} = 2\omega C U^2 = 2*100\pi*0.25*10^{-6}*50*130^2*10^6 = 132.73\,MVAr$$

$$Q_{130kVCables-consumption} = 2*3I^2 X_L = 2*3*870.13^2*100\pi*0.35*10^{-3}*50 = 25\,MVAr$$

From 20 kV cables of 13 feeders:

Ignore the cable segments between WTGs, each feeder has a 2 km cable segment connected to the 20 kV hubs, contributions from these cable segments are estimated:

$$Q_{20kVCables-production} = 13*\frac{U^2}{X_C} = 13*U^2\omega C = 13*20^2*100\pi*0.52*10^{-6}*2 = 1.7\,MVAr$$

$$Q_{20kVCables-consumption} = 13*3I^2 X_L = 13*3*904^2*100\pi*0.5*10^{-3}*2 = 10.01\,MVAr$$

Reactive power consumption of transformers can be calculated as in Section 2.3.4. The total consumption of four 20/130 kV transformers and two 130/400 kV transformers is found to be 66.46 MVAr.

Reactive power consumption of 130 WTGs:
$$Q_{130WTGs} = 130*0.9 = 117\,MVAr$$

It can be estimated that to balance reactive power, the system needs this amount of reactive power from compensation devices:
$$Q_{compensation} = Q_{130WTGs} + Q_{20kVCables\_consumption} + Q_{130kVCable\_consumption} + Q_{Transformers\_consumption}$$
$$- Q_{20kVCable\_production} - Q_{130Cables\_production}$$
$$= 117 + 10.01 + 25 + 66.46 - 1.7 - 132.73 = 83.58\,MVAr$$

This calculation gives a general idea about the size of compensation devices, more accurate calculations are performed with PowerWorld Simulator in Section 3.4.

3.3 Position of compensation devices

As previously mentioned, there is a large flow of reactive power from the system to the wind park. This reactive power flow increases the losses on the lines and transformers, causes the voltage drop over these components, and reduces active power transfer capacity of the system. In order to avoid this power flow, compensation devices should be installed as close to the wind turbines as possible. However, strongly distributed installation is not of interest due to installation and maintenance costs. The possible solution is to install at the 20 kV collection hubs. Capacitor banks are installed on the 20 kV side of sub-transmission transformers to compensate for reactive power consumption in steady state.

Additional compensation devices to help the wind park ride through faults are needed. These devices could be switched shunt capacitors, SVCs or STATCOMs which are marked as STATCOM in Figure 13. Position of these devices depends on the design purpose. A position close to the point of connection gives benefit on control of reactive power exchange since we can avoid losses on components. However, installing close to the WTGs gives better remaining voltage during faults in the transmission system. In this design, these devices are initially placed on the low voltage side (130 kV side) of transmission transformers as in Figure 13 and will be considered again in the second part of the project.
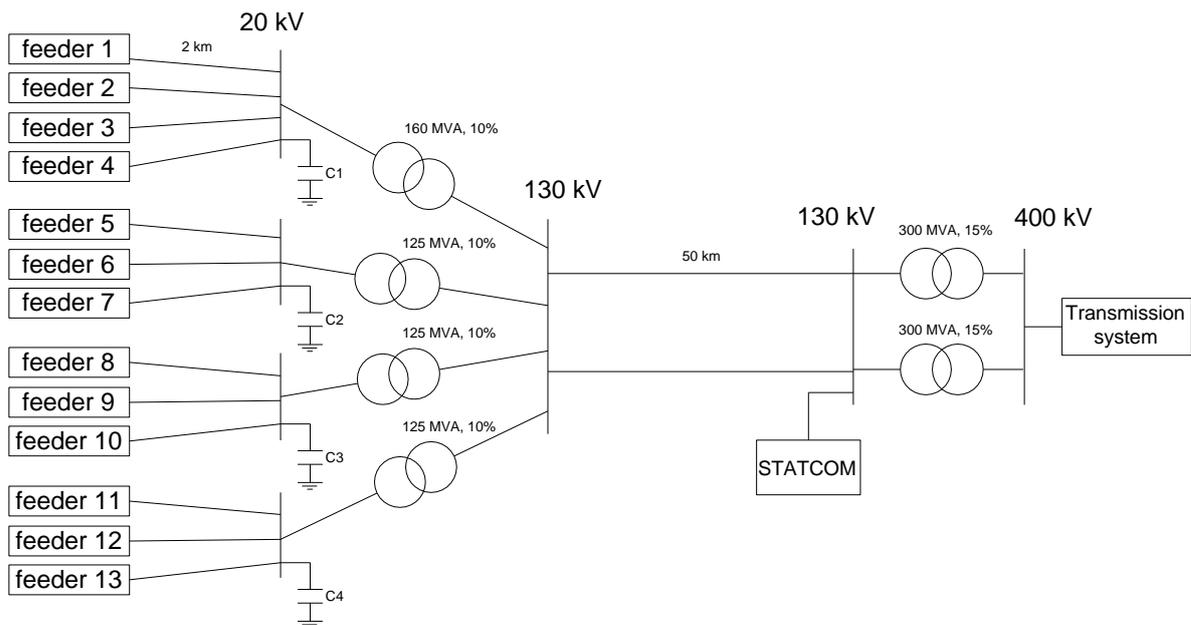
Figure 13   Position of compensation devices

3.4   Reactive power compensation

3.4.1 Power flow

The system is simulated with PowerWorld Simulator to find the needed size of reactive power compensation in different operating conditions. Simulations are implemented for four different generation cases and the results are given in Table 5. The STATCOM is modeled by a condenser to find the reactive power flow.

Table 5   Power flows from PowerWorld

Generation	10%	40%	70%	100%
C1, unit *	0	0	0	2
C2, unit *	0	0	0	1
C3, unit *	0	0	0	1
C4, unit *	0	0	0	1
STATCOM, MVAr	-131.882	-105.629	-45.377	0
P exchange, MW **	-38.526	-154.758	-269.983	-384.996
Q exchange, MVAr **	-0.424	0.353	-0.370	-3.454

*) One unit has a capacity of 10 MVAr
**) Negative values mean power flow from the wind park to the system, STATCOM consumes reactive power and vice versa.

Power flows from PowerWorld for the case of full generation are presented in Figure 14. A picture from PowerWorld Simulator is given in Appendix A.
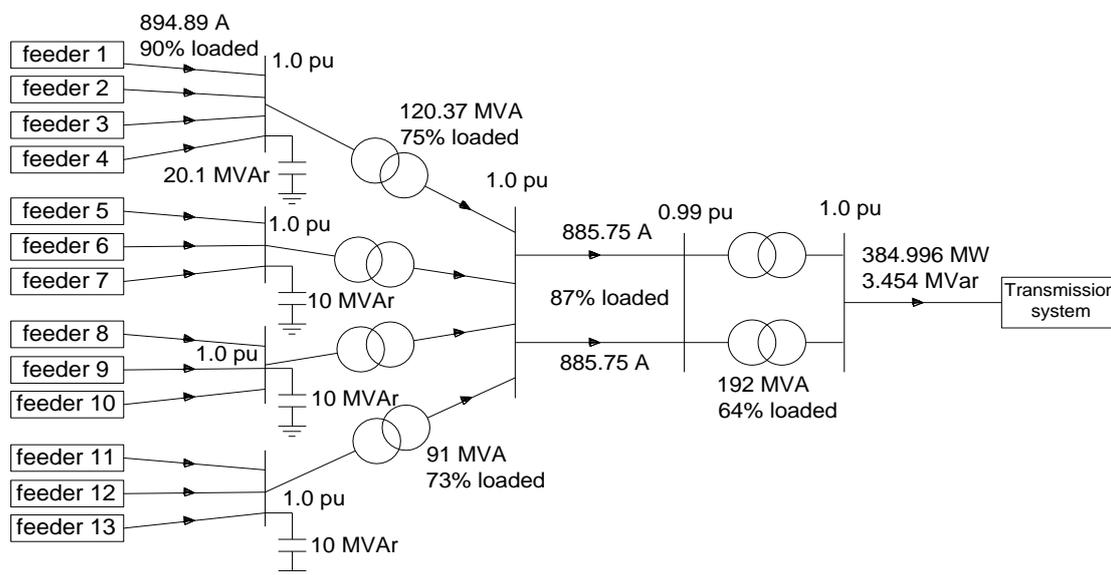
Figure 14   Power flows from PowerWorld at 100% generation

PowerWorld shows that the system is in normal operation, all bus voltages are within the permissible range and no component is overloaded which means that previous assumptions and calculations to select the components are correct.

3.4.2 Selection of compensation devices

From Table 5 we can see that at full generation, 50 MVAr reactive power from four capacitor banks is enough to compensate for the consumption of wind park to archive zero reactive power exchange at the PoC, there is no need to use STATCOM to produce reactive power in this operation case. In all other cases, there is a surplus amount of reactive power produced by the 130 kV cables which should be consumed. A switched shunt reactor or a regulated reactor can do this job. A number of reactors plus a smaller STATCOM could also do the job. Therefore, the size of STATCOM is selected according to the ride-through capability which will be considered later in the second part of this study. The sizes of capacitor banks are given in Table 6.

Table 6   Compensation ratings

Compensation devices	C1	C2	C3	C4
Capacity, MVAr	2x10	1x10	1x10	1x10

Part 2: Dynamic Analysis

1 Introduction

In this part, dynamic behaviors of a single induction machine as well as the whole system will be analyzed. The voltage tolerance curves (voltage dip profiles) in different scenarios are figured out to study the ride-through capability of single machine as well as the whole wind park. All simulations are implemented with PSCAD/EMTDC.

2 Behavior of single induction machine

2.1 Machine model

The model used is induction machine model in EMTDC. Refer to the parameters of a similar induction machine model in [8], the following parameters are applied.
MVA rated: 3.5 MVA, MW rated: 3 MW, U rated: 690 V
Stator resistance: 0.048 pu
Stator reactance: 0.075 pu
Rotor resistance (1st cage): 0.298 pu
Rotor reactance (1st cage): 0.12 pu
Rotor resistance (2nd cage): 0.018 pu
Rotor reactance (2nd cage): 0.105 pu
Magnetizing reactance: 3.8 pu
Inertia constant: 3.5 sec (including machine rotor and wind turbine)

2.2 Torque speed curve and operating point of induction machine

An equivalent circuit is needed to study torque-speed curve of induction machines. Conventional models of induction machines use a fixed value of rotor resistance. However, the induction machine model in EMTDC has two cages. According to [9], the equivalent circuit of induction machines with two cages or deep-rotor-bar effect is presented in Figure 15.
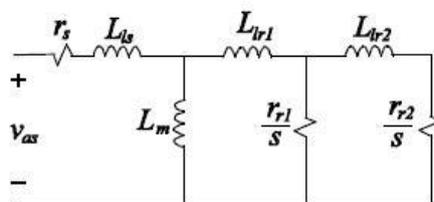

Figure 15 Equivalent circuit of induction machine [9]

r_s , L_{ls} : stator resistance and leakage reactance
r_{r1} , L_{lr1}: rotor resistance and leakage reactance, transformed to stator side, first cage
r_{r2} , L_{lr2}: rotor resistance and leakage reactance, transformed to stator side, second cage
L_m : magnetizing reactance
s: slip

The equivalent value of rotor resistance changes with the slip or rotor speed which is difficult to estimate due to lack of information of the model in EMTDC. However, the shape of equivalent torque-speed curve can be approximated by two curves corresponding to two values of rotor resistances.

For each value of rotor resistance, the developed torque of induction machine can be obtained by dividing the mechanical power by shaft speed. All of these calculations are clearly stated in [10]. Using these equations to write a Matlab code, the Torque-Speed curve is plotted in Figure 16.
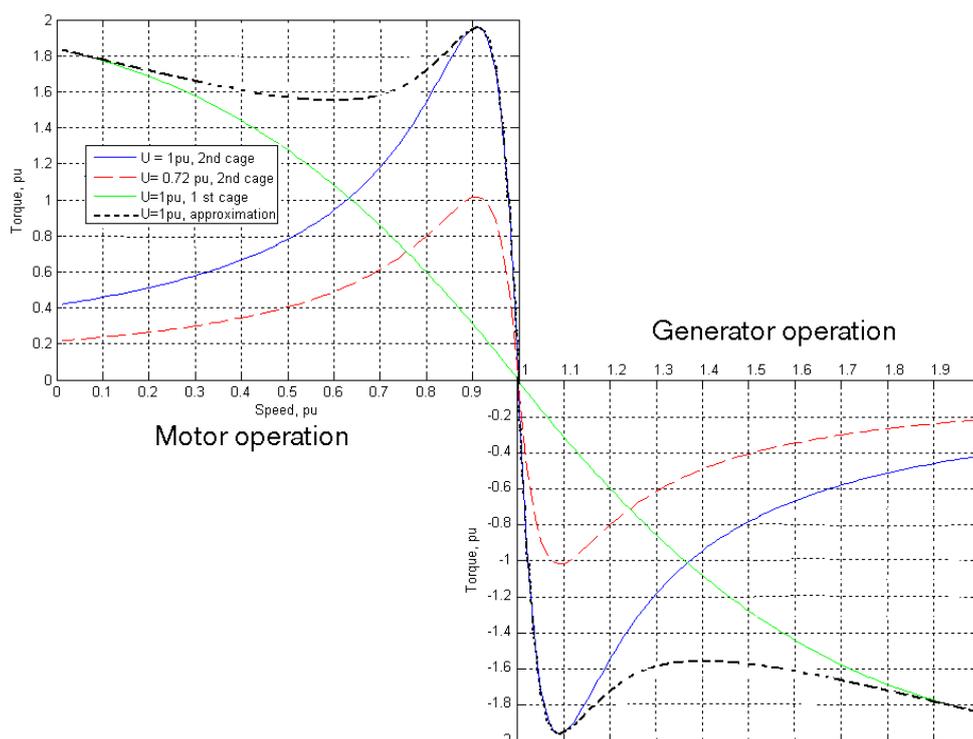
Figure 16 Torque speed curve of machine

At starting, operating point follows the curve with first cage resistance to increase starting torque. As the speed close to rated speed, it follows the curve of second cage resistance to reduce losses. The pull-out torque at 1 pu and 0.72 pu voltage is approximately 1.95 pu and 1 pu, respectively. This means that if the machine is operating at 1pu torque, assume no torque control, it dies out at 0.72 pu voltage dip. The stable operating points in generator mode should be between 1 pu and the speed at pull-out torque.

During the dip, induction machines speed up due to the difference in mechanical and electrical torques as shown in the swing equation:

$$J \frac{d\omega}{dt} = T_m - T_e$$

J: moment of inertia, ω: angular speed, T_m: mechanical torque, T_e: electrical torque

If dip duration is short enough (less than or equal to critical dip duration), machine speeds up but it is able to go back to its previous operating point.

Immediately after the dip, the induction machine draws a large amount of reactive power from the system to build up magnetic field in the air gap. It is very important that the system must be strong enough to supply this amount of reactive power to help the machine recover. This can be seen the Figure 18 in Section 2.3.

Thus, it is obvious that ride-through capability of induction machine depends on many parameters: depth and duration of dips, inertia constant of machine, pre-fault operating point, and strength of the system to which the machine is connected.

2.3   Simulation setup and results

Setup of induction machine in low voltage system with EMTDC is shown in Figure 17.
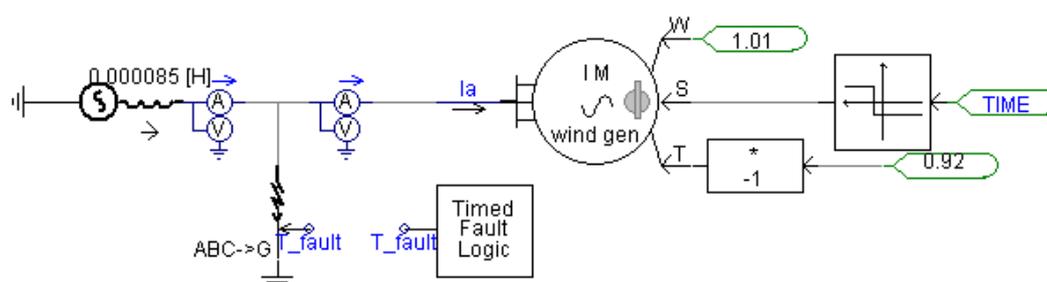
Figure 17 Single induction machine in low voltage system

Two faults are applied, one lead to instable operation of the machine and the other with stable operation. The voltage, power, torque and speed curves of these two cases are presented in Figure 18.

In order to plot the voltage tolerance curve, different fault levels and durations are applied with different scenarios by changing inertia constant H, short circuit ratio, and pre-fault operating capacity of machine. Critical fault durations are given in Table 7.

Table 7 Critical faut durations for single machine

Remaining voltage, pu	0	0.1	0.2	0.3	0.4	0.5	0.55	0.6	0.65	0.7
SCR=10, P=100%, H=3.5 sec	0.54	0.56	0.63	0.73	0.90	1.19	1.43	2.64	7.5	#
SCR=10, P=100%, H=5 sec	0.70	0.79	0.86	1.00	1.23	1.63	2.21	3.63	10.0	#
SCR=10, P=100%, H=0.5 sec	0.10	0.11	0.14	0.18	0.22	0.27	0.33	0.47	0.71	#
SCR=10, P=70%, H=3.5 sec	0.82	0.84	0.92	1.04	1.26	1.66	2.57	5.01	#	#
SCR=5, P=100%, H=3.5 sec	0.20	0.22	0.25	0.29	0.37	0.54	0.66	0.84	1.32	#

The table shows critical fault durations for different scenarios. "#" means machine can withstand this voltage for any duration without losing stability.
SCR: Short circuit ratio. P: generating of machine, H: inertia constant
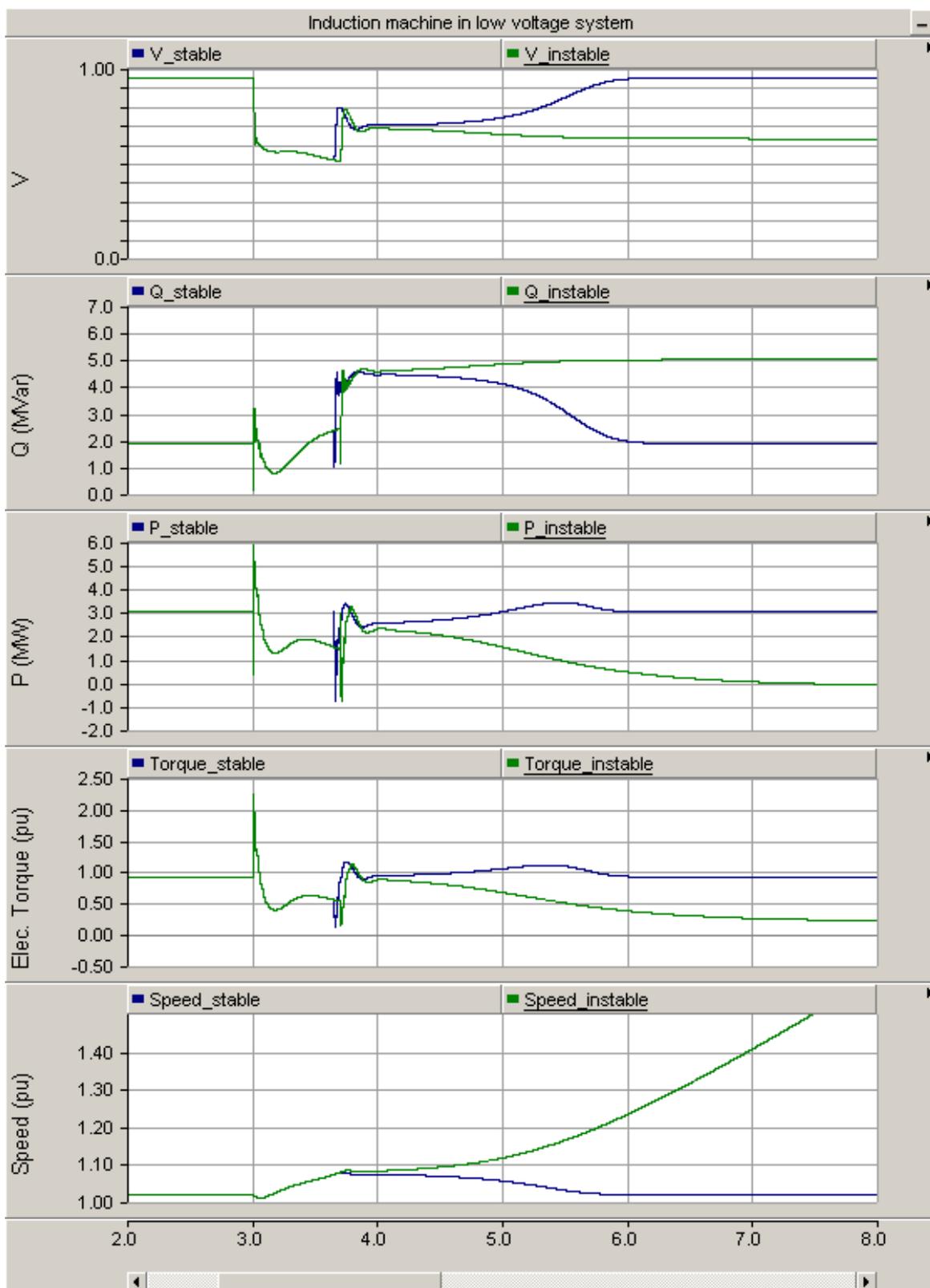
Figure 18 Stable and instable operations of induction machine

*** Influence of the inertia constant**

Three values of inertia constant are taken into consideration: 0.5 sec (induction machine alone), 3.5 sec (induction machine with medium wind turbine), and 5 sec (induction machine with large wind turbine) [8]. The short circuit ratio is 10 and the machine is operating at full capacity. Voltage tolerance curves are shown in Figure 19.
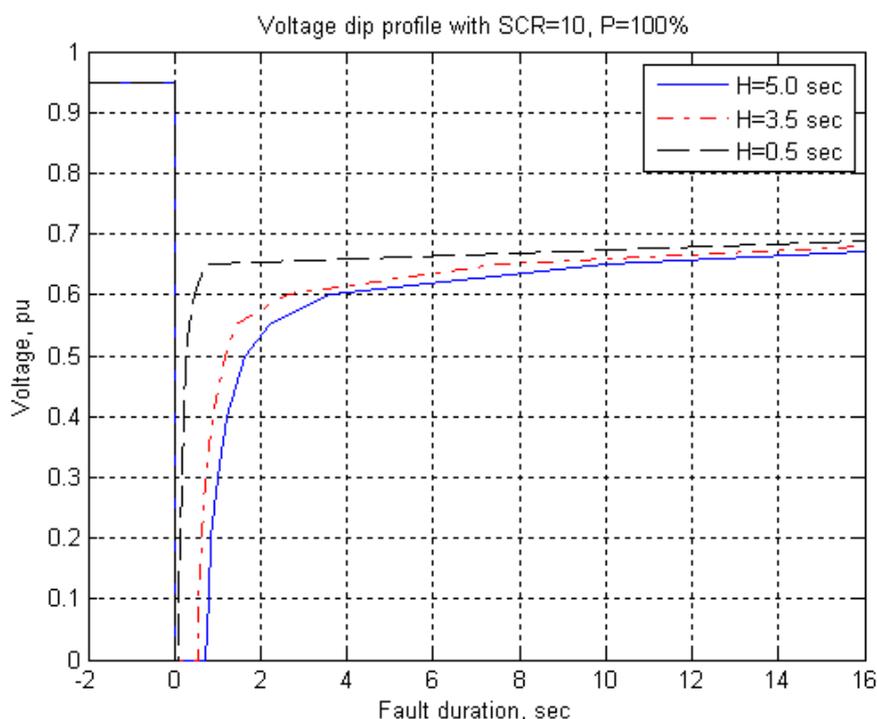
Figure 19 Voltage tolerance curve with different values of inertia constant

From these plots, one can see that the machine with higher inertia have better ride-through capacity. This could be explained that a machine with bigger rotor accelerates slower according to the swing equation in Section 2.2. The machine used in this project with H = 3.5 sec is able to withstand zero voltage up to 0.54 sec and 0.7 pu voltage for any duration without losing stability.

*** Influence of the pre-fault operation point**

With the same condition, simulations for the cases with 100% and 70% capacity are implemented. Voltage tolerance curves are plotted in Figure 20.

We can see that a decrease of 30% in generated power leads to an increase of approximately 40% to 50% of critical fault duration. This is due to the fact that lower power (pre-fault) gives large stable margin. For a wind turbine, the produced power is less than 100% during a large fraction of time. Thus, we can expect better ride-through capacity of a real wind park.
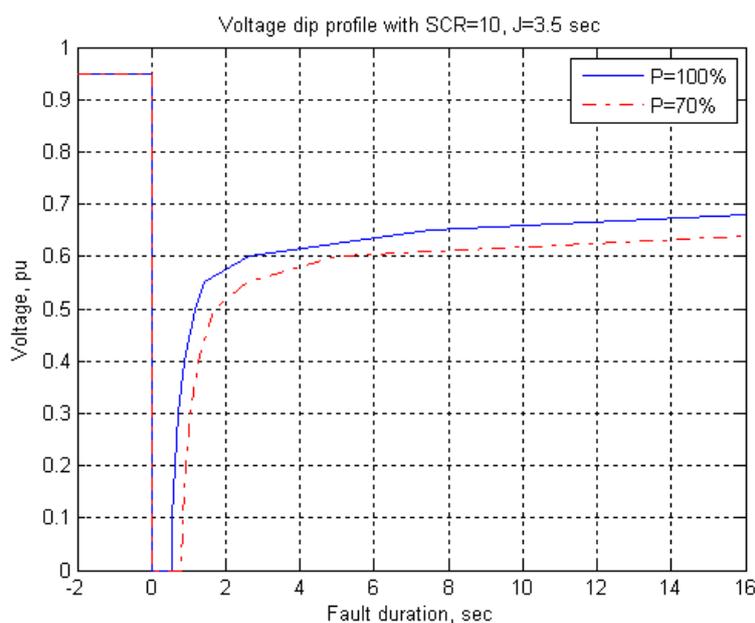
Figure 20 Voltage tolerance curve with different values of generated power

*** Influence of the short-circuit ratio***

As mentioned previously, behavior of induction machine depends on the strength of the system to which it is connected. The system strength is measured by the ratio between the short-circuit capacity of system and rated power of machine, which is known as short circuit ratio (SCR). Figure 21 represents voltage tolerance curves in the same conditions with two values of SCR, 5 and 10.
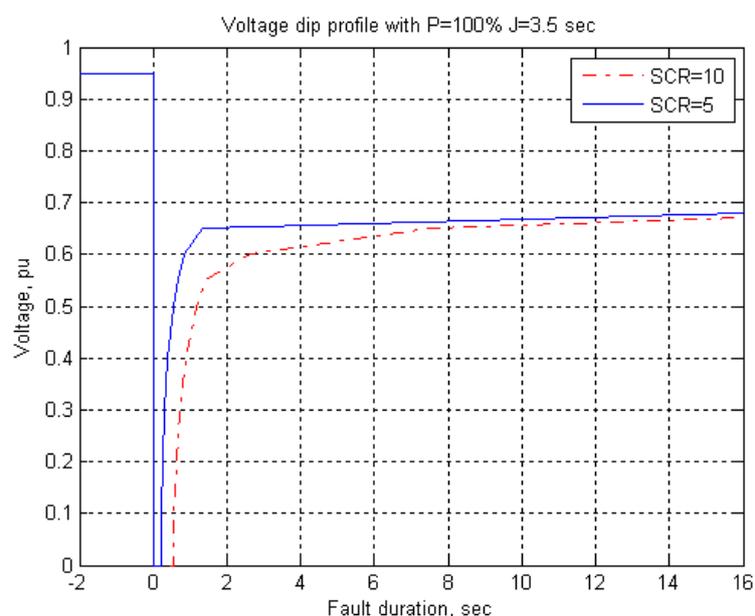
Figure 21 Voltage tolerance curve with different values of SRC

We can see a decrease of 50% in SCR approximately leads to a decrease of 50% to 60% in critical fault duration. This is due to the fact that a weak system has limited capability of supplying reactive power to help the machine go back to stable operating point.

3 Behavior of one feeder

3.1   Model of wind turbine generator

The model used in this project is fixed-speed induction machine directly connected to the grid in EMTDC. The turbine rated at 3 MW is equipped with a pitch angle controller. Induction machine is initially started with speed control to reach steady state and switched to torque control at one second. Pitch angle dynamic control is applied at 5 second. The whole system model in EMTDC can be seen in Appendix B.

As previously mentioned in part 1 of this project, reactive power consumption of magnetizing branch of induction generator is compensated by a shunt capacitor. In EMTDC simulation, at zero active power generating, reactive power consumption is 0.95 MVAr. Thus, a 0.95 MVAr shunt capacitor is installed at the generator terminal.

3.2   Feeder setup and simulation results

Arrangement of one feeder of 10 WTGs can be seen in Appendix C. At this step, WTG model is fixed with inertia constant equal to 3.5 sec. The wind park is assumed to be operating at full capacity. Short circuit ratio at the terminal of the wind park (where the fault is applied) is changed to study RTC. Simulation results are presented in Table 8 and Figure 22. Note the difference in horizontal scale compared to the figures in the previous section.

Table 8 Critical fault durations of one feeder

| Remain voltage, pu	0	0.2	0.4	0.6	0.7	0.8	0.9	0.95
SCR = 10	0.04	0.06	0.07	0.11	0.16	0.29	0.74	#
SCR = 20	0.06	0.08	0.09	0.16	0.23	0.43	1.07	#
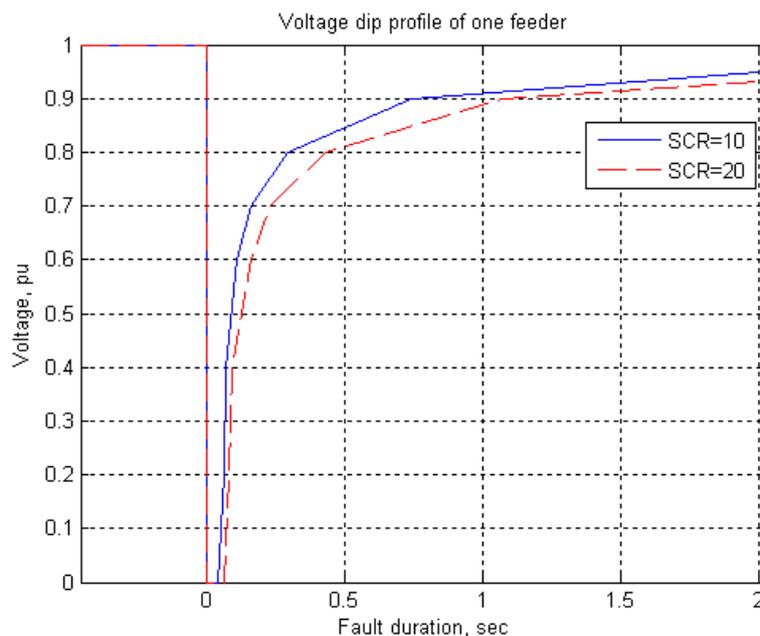
Figure 22 Voltage dip profile of one feeder

One can see that the fault tolerance of one feeder is much lower than that of single machine because the machines are now connected to a weaker system. This is due to the fact that the total impedance between the voltage source and the machine has remarkably increased.

Due to a large number of machines in the wind park, it is not convenient for a project like this to use the full model with 130 WTGs because it requires a lot of computer resources to do simulations. Thus, aggregated model is of interest. The methods of aggregation are presented in Section 4.

4 Model aggregation

In order to reduce the size of the system in simulation, aggregated model of several similar machines is usually used. However, this will introduce some error which needs to be estimated. In this section, the aggregation methods and error estimation are studied. As a result, the final aggregated model for the wind park is obtained.

4.1 Aggregation Methods

Considering ten 3MW machines in one feeder, as shown in Figure 23, two aggregation methods will be considered:

- Method 1: merging ten 3MW machines into one equivalent machine with capacity of 30MW and introducing an additional cable segment between the machine and the terminal of 2 km 20 kV cable. This additional cable segment is needed to compensate for the fact that different machines are subjected to different voltages during the fault in the system. Also after the fault (during the acceleration stage) are the different machines exposed to different voltages. As a result, the machines accelerate differently. Using the single-machine equivalent model means that the machines are supposed to be subjected to the same voltage. This introduces an error compared to the full model. Thus, it is necessary to study the influence of the length of this additional cable section on the error to find the length that gives the smallest error.

- Method 2: neglecting the cable segment between nodes 5 and 10, merging two 3MW machines with similar distance to the 20 kV hubs into one 6MW machine, using half the impedance of the cable segments between the machines.
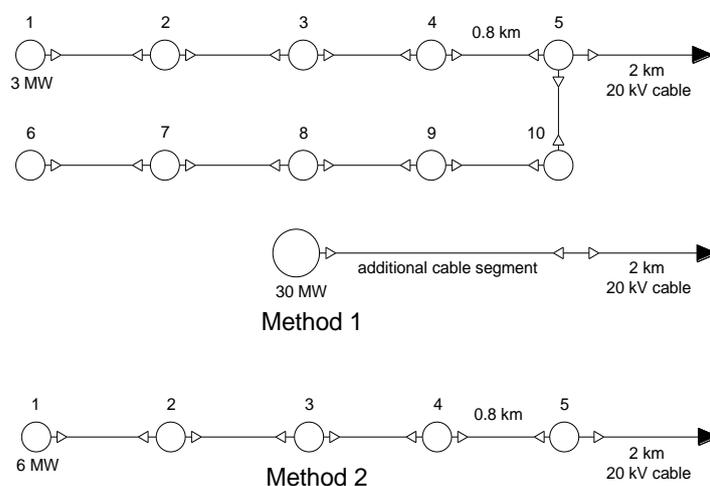
Figure 23 Aggregation methods for one feeder

4.2 Error estimation

In order to see the influence of the additional cable segment in Method 1, the 30 MW machine is placed at different positions. At 25 second, the same fault (three-phase, zero fault resistance, 60 ms duration) is applied at the point of connection for different cases. Simulation results show that there are no big differences in active power and voltage. However, reactive power error is quite large, especially during the fault. A graph showing these errors between the full model and the reduced model with 1.6 km additional cable segment is plotted in Figure 24.
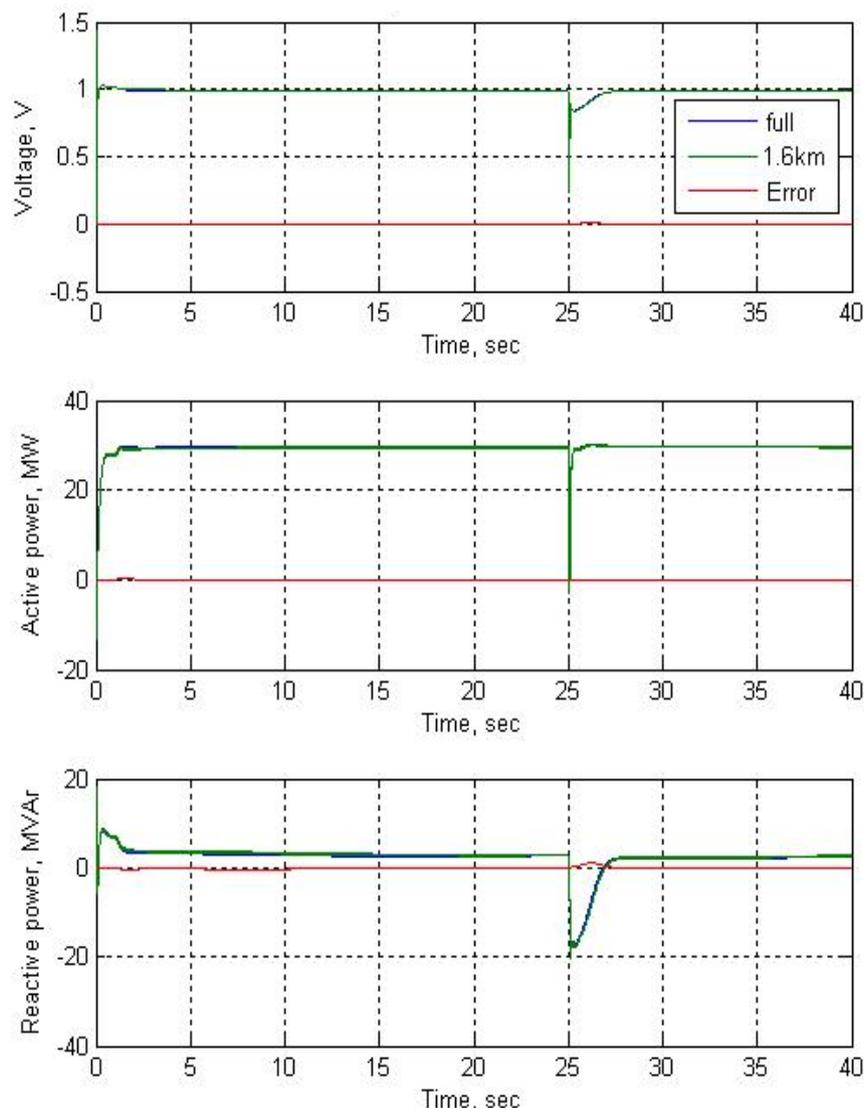
Figure 24 Errors of V, P, Q

Since reactive power error is mostly concerned, error in percent of reactive power exchange with the system for different cases compared to the full model are shown in Figure 25. There are four cases, named as:

- "5 units" represents the case of Method 2.
- "0 km", "1.6 km", and "3.2 km" represent the cases of Method 1; the equivalent machine is placed at nodes 5, 3, and 1, respectively.
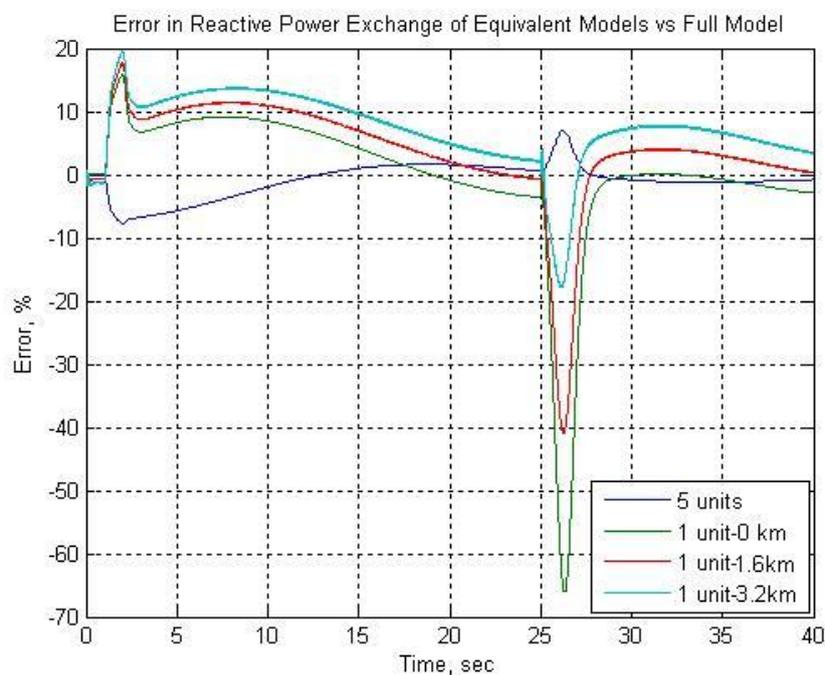
Figure 25 Reactive power exchange error

In most of the cases of Method 1, the error reaches more than 10% in normal operation and up to 66% during the fault while Method 2 gives a much better agreement; the error is less than 10% both in normal operation and during fault.

From this result, one can see that by using Method 2, the similar machines subjected to the same voltage dip are merged into one aggregated machine. Thus, this method gives better agreement and is used to reduce the size of the model in this study.

4.3   Aggregated model

By using Method 2 mentioned previously, a reduced model can be built. Four feeders in Group 1 can be merged into one. Thus, Group 1 now includes five equivalent machines with capacity of 24 MW. The same rule is applied for Groups 2, 3, and 4. Since each group has three feeders, there are five 18 MW equivalent machines in each feeder. At this step, the model includes twenty equivalent machines which still take long time to complete a simulation. The next step is to merge four groups into one to come up with the final model including five equivalent machines with capacity of 78 MW each.

However, this 5-unit model again requires long simulation time when the SVC is included. In addition, the main objective of the coming section is to study the influence of reactive power supporting devices. Thus, the model again is reduced to 2-unit model; each unit has a capacity of 195 MW. Two units represent for the two groups of WTGs, one close to and one far from the 20kV hub which are subjected to different dip levels during faults in the system.

The verification of the two-unit against the five-unit model in the extent of ride-through capability is implemented; the critical fault durations are shown Table 9.

Table 9 Critical fault durations 2-unit vs. 5-unit model

V_remain, pu	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
5-unit model	0.08	0.08	0.09	0.10	0.12	0.15	0.19	0.30	0.50	1.50	#
2-unit model	0.08	0.08	0.09	0.10	0.12	0.15	0.19	0.31	0.52	1.65	#

From this verification, there is no significant difference in critical time of the two models, especially with the dips less than 0.7 pu which are the most interested cases to study RTC. Thus, it can be concluded that the 2-unit model is good enough for general study of RTC of wind parks. However, when verifying the RTC of a real wind park, it is recommended that a more detailed model is used.

5 Ride-through capability of wind park and grid code compliance

5.1 Ride-through capability of wind park without additional supporting device

The reduced model from Section 4 (the model with two equivalent units) is used to study the RTC of the wind park. Reactive power consumption in normal operation is compensated by five capacitor banks at 20 kV hubs as in Figure 13 with total capacity of 50 MVAr to archive zero reactive power exchange at the PoC.

It is convenient to note that any amount of additional reactive power compensation for the system excludes 50 MVAr from the mentioned capacitor banks. Thus the term "the wind park without additional supporting device" means the wind park itself plus 50 MVAR capacitor banks at 20 kV hubs. In other words, these capacitor banks are connected and fixed during the study. The MVA base used for per-unit calculation is 455 MVA which is the rating of the wind park. Ride-through capability is studied for the wind park at full generation and SCR of 20.

The simulations of the wind park are implemented and the critical fault durations are recorded in Table 10.

Table 10 Critical fault durations of the wind park

Dip, pu	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.95
Durations	0.08	0.08	0.09	0.10	0.12	0.15	0.19	0.30	0.50	1.50	#

This voltage tolerance curve and the Grid Code requirement [3] are plotted in Figure 26.
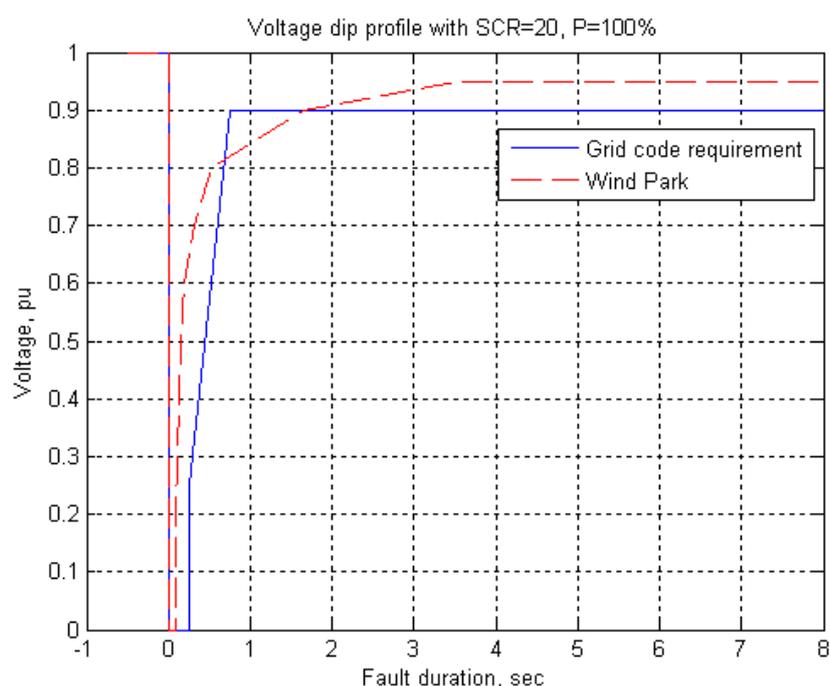
Figure 26 Voltage tolerance curves of Wind Park and Nordel Grid Code

From these curves, one can see that the tolerance of the wind park is far from the Grid Code requirement. In addition, the wind park cannot withstand low operating voltages; it collapses at voltages less than 0.95 pu. Thus, additional reactive power supporting devices are needed to help the wind park ride through the most severe faults. There are several techniques dedicated to this application which are presented in the next section.

5.2   Reactive power compensation techniques for wind parks

In this section, several solutions of reactive power compensation to improve RTC of wind parks are taken into consideration. Simulation results and grid code compliance will be presented.

According to [11], during the fault at the point of connection, the system is de-facto in island operation so that the control options are very limited. After the fault, sufficient reactive power sources are very important to bring induction machines back to their normal speed. Thus, any reactive power source which can be switched on fast enough may be a possible solution to RTC of wind park. The possible solutions mentioned in [11] include switched shunt capacitor, SVC, and STATCOM.

The locations of compensation device are also taken into consideration, one on the 130 kV side of the onshore 130/400 kV transmission transformers and one on the 20 kV side of the 20/130 kV transformers on the offshore platform.

5.2.1 Switched shunt capacitor

Switched shunt capacitor is the cheapest solution. However, the drawbacks include slow response and non-smooth control range which are mentioned later in this section.

It is important to estimate the needed size of capacitor bank. The fault is assumed to be three-phase and zero-impedance. Initially, the capacitor bank is placed on the 130 kV side of transmission transformers. Different fault durations are applied and for each case, the size of capacitor bank is varied to find the critical value which is able to help the wind park ride through. In these simulations, it is assumed that the capacitor bank can be switched on 40 ms after the fault occurs and switched off when the voltage recovers to certain levels which will be mentioned later in this section. The size of capacitor and the critical fault duration are given in Table 11 and Figure 27.

Table 11 Critical fault durations of the wind park with different sizes of capacitor bank

| Size, MVAr	0	100	200	400	455	682.5	**730**	910	1365	1500	1593
pu.	0	0.22	0.44	0.88	1.00	1.50	**1.60**	2.00	3.00	3.30	3.40
Critical time	0.08	0.10	0.11	0.15	0.16	0.22	**0.25**	0.33	0.56	0.66	10
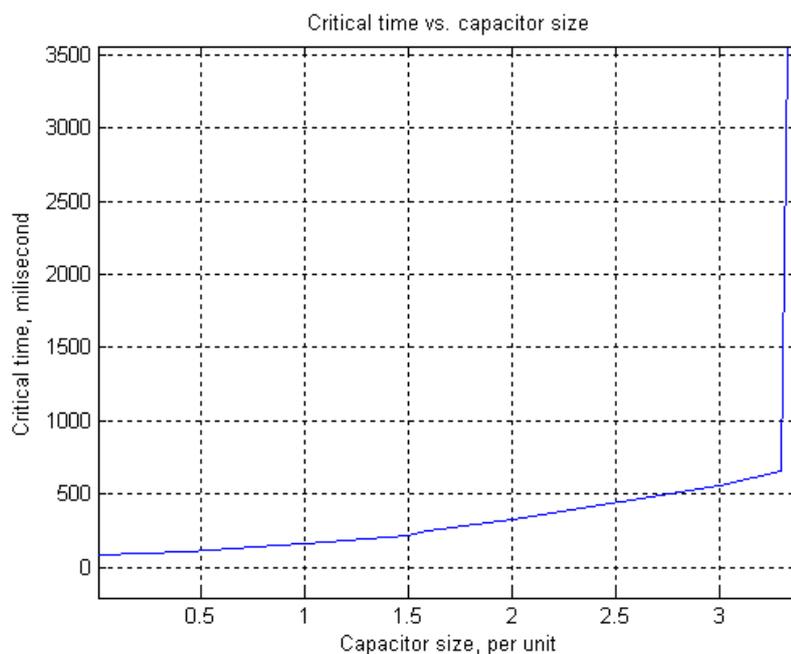
Figure 27 Capacitor size vs. critical fault duration

From the simulations, with 1.6 pu reactive power compensation, the system can withstand zero voltage for 250 ms as required in the Grid Code. The results also show that the more reactive power available, the longer the critical fault duration; and theoretically, if there is enough reactive power to support after the fault, the system can withstand the fault for any duration. In this simulation, 3.4 pu reactive power can help the system withstand zero voltage dip for any duration. However, there are several drawbacks of this solution which need to be solved this can be implemented practically:

- The ability of reactive power control is limited.

- The system has to be subjected to significant over current during the fault and over voltage immediately after the fault.

- The transient during switching must be taken into consideration, especially when the size of the capacitor bank is large. Harmonic resonances may occur when the capacitor banks are connected. Combination of smaller banks would be a possible solution; and it requires a controller.

- The point at which the capacitor bank is switched off must be calculated to make sure that the system will not collapse when the capacitor bank is removed. The voltage curves of two cases (recover: V_1.05 and collapse: V_1.0) are presented in Figure 28. In the former, the capacitor bank is removed at the point when voltage at the 20 kV hubs recovers to 1.05 pu and 1.0 pu for the latter.
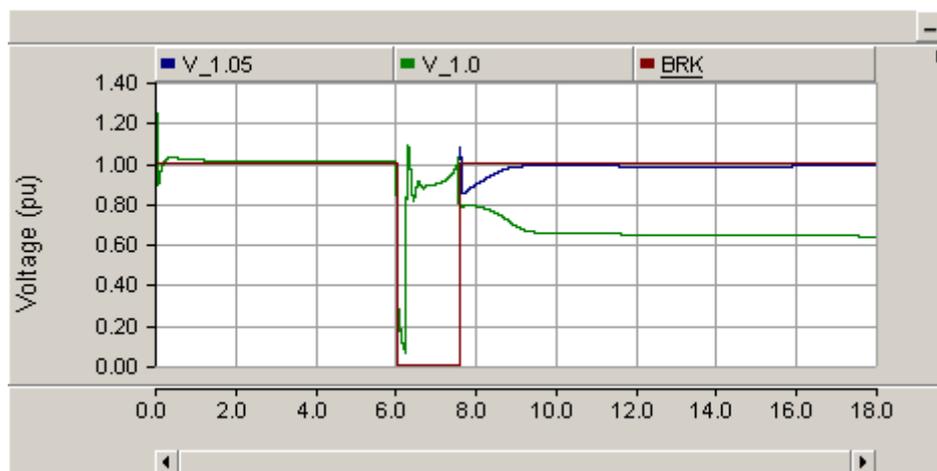
Figure 28 Voltage recovery with switched shunt capacitor

(BRK: breaker control signal (1: OFF, 0: ON))

In the former case, the system can survive, there is, however, a large voltage drop (down to 0.85 pu) when the capacitor bank is removed and it needs approximately 1.6 sec to go back to its normal value. This may lead to under-voltage or over-current problems. The situation can be improved by dividing the capacitor into smaller units and switching off one by one. The voltages of the case with one capacitor unit and the one with three units are plotted in Figure 29. Note different time scale compared to Figure 28.
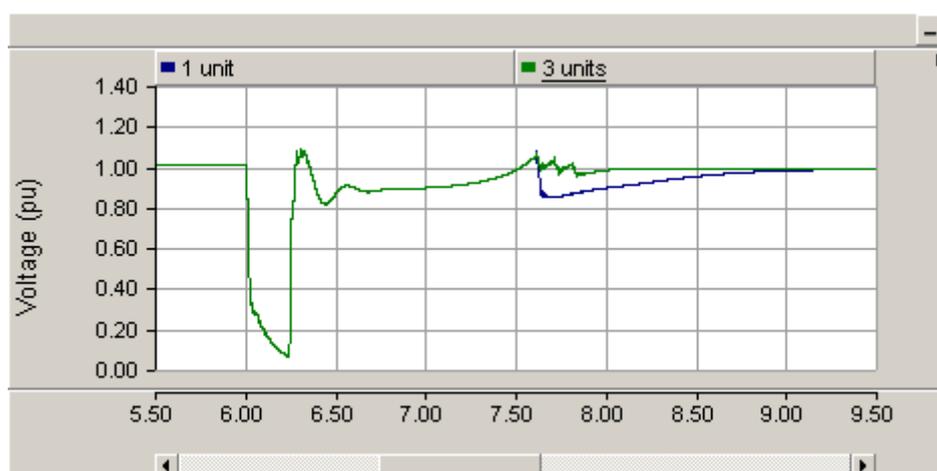

Figurer 29 Voltage recovery with different numbers of capacitor banks

Another important factor to be considered is the point at which the capacitor is switched on. This time depends on the dip detection logic and the speed of switching devices. The voltage recovery curves for different switching delays are plotted in Figure 30. The fault duration is 240 ms. There are three switching instants, one before the fault clearing (40 ms) and two after the fault clearing (255ms and 260 ms).
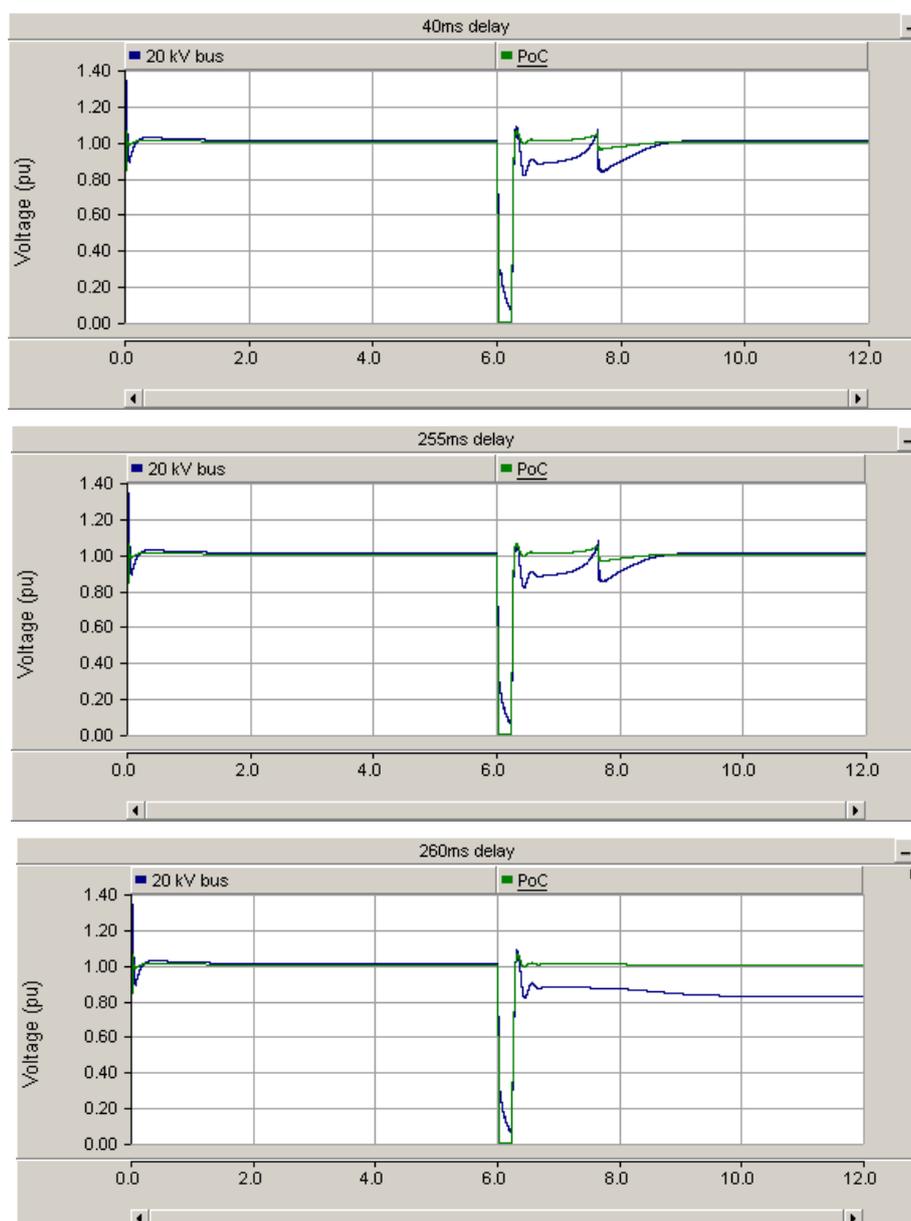
Figure 30 Voltage recover curves for different switching points of capacitor.

One can see that there is no need to switch on the capacitor very fast. Switching on at 40ms or 255ms after the fault occurrence gives the same effect on system recovery. Longer delay (example 260 ms) leads to voltage collapse.

To see the influence of position of capacitor bank, the same study is implemented for the case the capacitor bank is placed on the 20 kV side of the offshore 20/130 kV transformers. It is found that at this position, the needed size for the capacitor reduces to 1.2 pu instead of 1.6 pu.

5.2.2 SVC

The reactive power consumption or production of an SVC is proportional to square of voltage like switched capacitors and reactors. If the controller is good enough, an SVC can give very fast response and quickly produce the maximum reactive power like a switched capacitor. The main difference is that an SVC is able to control reactive power or voltage smoothly by combinations of different TSCs and firing angles of TCR. An SVC model from [12] which is made of four TSCs and one TCR are applied to the system. Simulation results for the systems with 1 pu SVC, 1 pu capacitor bank (CAP), and no supporting device are shown in Figure 31.
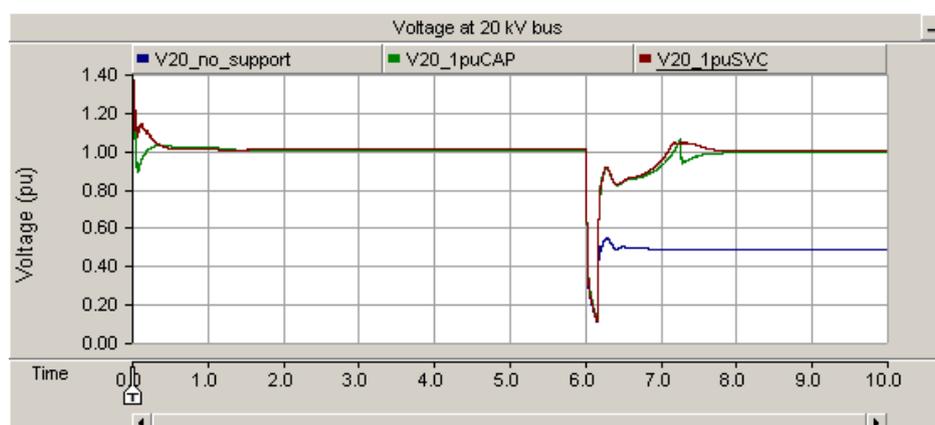

Figure 31 Voltage recovery with different supporting devices

Here one can see that compared to the capacitor bank, the SVC is able to avoid sudden voltage drop.

To study the influence of SVC and its size on RTC, the same procedure as in the case of switched capacitor bank is applied. Simulation results show that it requires a 1.6 pu SVC to help the system ride through zero voltage in 250 ms, which is the same size needed for a capacitor bank. Critical fault durations for two cases are given in Table 12; no difference is recorded. This means that they have identical voltage tolerance curves which are presented graphically in Section 5.3.

Table 12 Critical fault durations of the wind park

V_remain, pu	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
1.6 pu Cap.	0.25	0.27	0.30	0.34	0.40	0.54	0.74	2.18	#
1.6 pu SVC	0.25	0.27	0.30	0.34	0.40	0.54	0.74	2.18	#

It can be concluded that, both SVC and switched capacitor are able to help the wind park meet the Grid Code requirement on RTC. However, it is also required that the system is able to smoothly control reactive power flows as well as voltages. This requirement cannot be fulfilled by a capacitor itself.

5.2.3 **STATCOM**

In this study, the STATCOM is modeled by a controllable voltage source behind an impedance Z as in the Figure 32. The power electronic valves are not modeled. Instead, the voltage source converter is modeled as a voltage source.
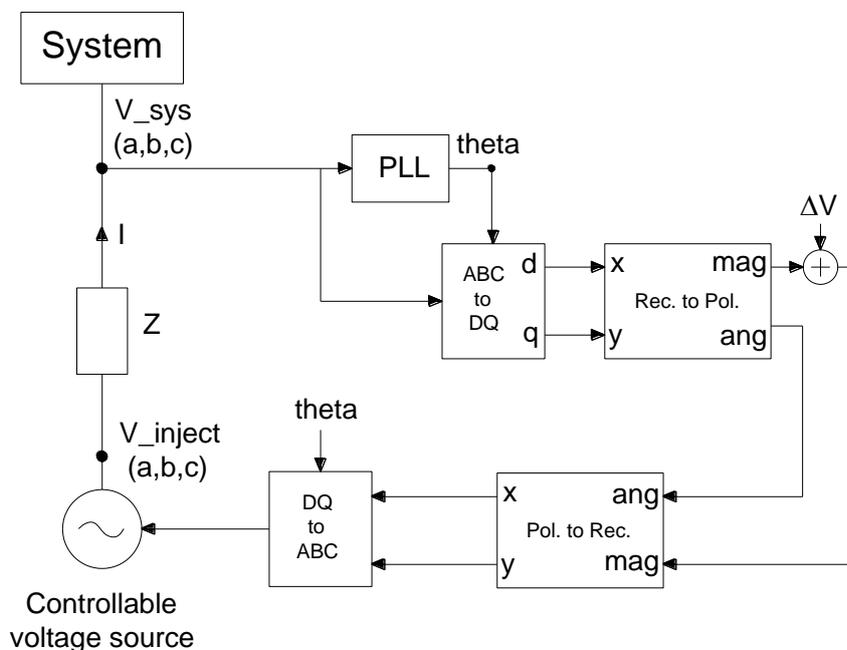

Figure 32 STATCOM model

V_sys (a,b,c): measured phase-to-ground voltages
V_inject (a,b,c): injected phase-to-ground voltages
ΔV: the voltage magnitude over the impedance Z controlling the amount of reactive power exchange, $\Delta V = V\_inject - V\_sys$
theta: angle of system voltage vector
PLL: Phase Lock Loop
Pol. To Rec., Rec. to Pol.: Polar to Rectangular and vice versa.
ABC to DQ, DQ to ABC : Park & Clarke transformations
I: injected current, $I = \Delta V/Z$

The magnitude difference between the system and injected voltage vectors (ΔV) decides the amount of reactive power exchange. The angle difference decides the active power exchange which is controlled to be zero.

To implement this scheme, the system voltage angle is tracked by a Phase Lock Loop (PLL). The measured system phase voltages are transformed into dq coordinates to control the magnitude and transformed back to phase voltages to apply to the controllable voltage source. By this method, the injected voltage always has the same frequency and angle with the system voltage. The only difference is the magnitude which controls reactive power flow. This model is expected to behave like a STATCOM

Different values of injected current are applied to find the current needed to meet the Grid Code requirements. It is found that there is no difference in the needed size for an SVC and a STATCOM to ride though zero voltage in 250 ms. It is found to be 1.6 pu. Although during the fault, the STATCOM produces a little more reactive power than the SVC but it does not help much because after the fault clearing, the system still needs a certain amount of reactive power to recover. The behaviors of the system with a 1.5 pu SVC and a 1.5 pu STATCOM are presented in Figure 33. Both show the cases of collapse.
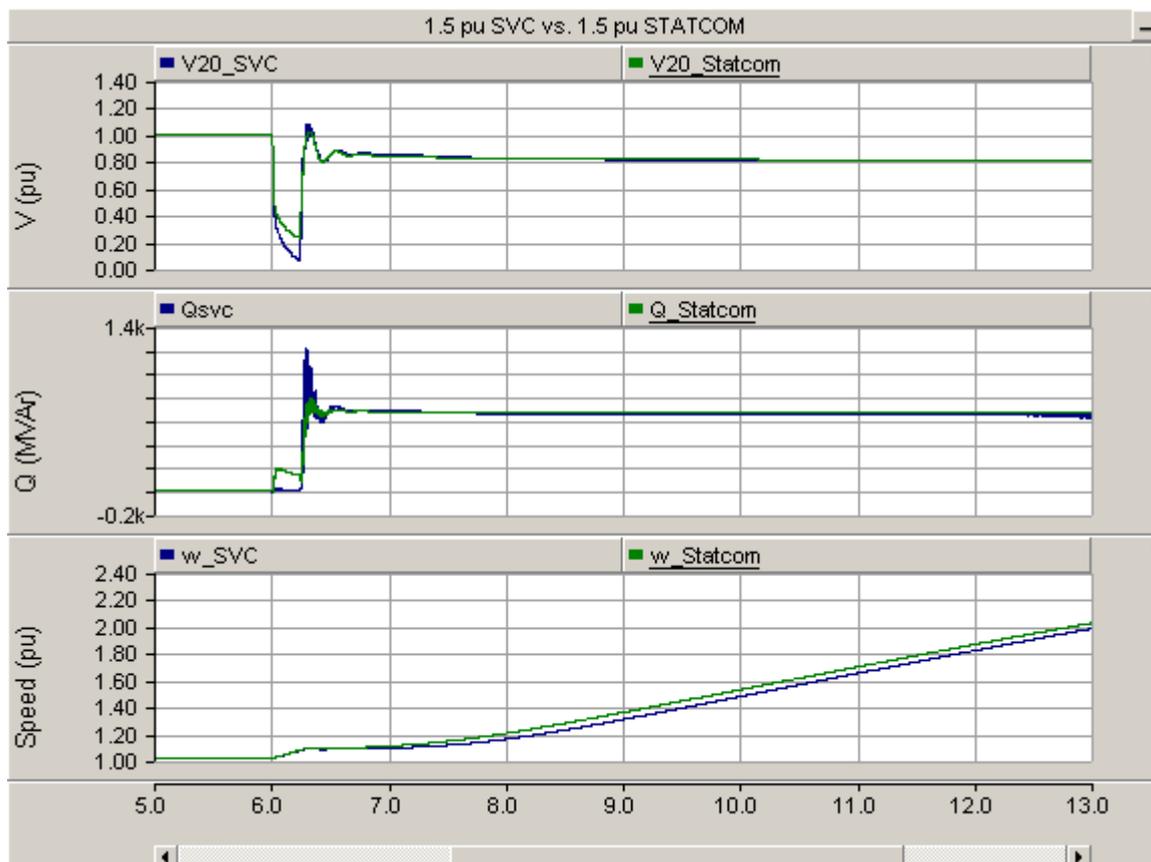
Figure 33 System behaviors with 1.5 pu SVC and 1.5 pu STATCOM

However, if the 1.5 pu STATCOM is controlled to be overloaded 20% in 1 sec, the system is able to recover. From this point, again, it can be seen that any amount of available reactive power right after the fault clearing is very important to help the system ride through.

In order to plot the voltage tolerance curve for the STATCOM, the same procedures as the case of SVC and switched shunt capacitor are applied. The results are given in Section 5.3.

Similar to the case of switched shunt capacitor or SVC, if it is installed on the 20 kV side of 20/130 kV offshore transformers, the required size for the STATCOM reduces from 1.5 pu to 1.0 pu.

5.3   Grid code compliance and summary

Different simulations of the system with switched shunt capacitor, SVC, and STATCOM has been implemented to study the ride-through capability. Critical fault durations and voltage tolerance curves for the system are given in Table 13 and Figure 34. These curves are built for the cases the supporting devices are installed on the 130 kV side of 130/400 onshore transformers.

Table 13 Critical fault durations of the wind park

| V_remain, pu	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.85	0.9	0.95
No support	0.08	0.08	0.09	0.10	0.12	0.15	0.19	0.31	0.52	-	1.65	#
1.0 pu SVC / Cap.	0.15	0.17	0.2	0.23	0.27	0.36	0.48	0.86	4.25	-	#	
1.6 pu SVC/ Cap.	0.25	0.27	0.30	0.34	0.40	0.54	0.74	2.18	6	#		
1.5 pu STATCOM	0.25	0.31	0.37	0.43	0.51	0.71	1.09	4.0	#			
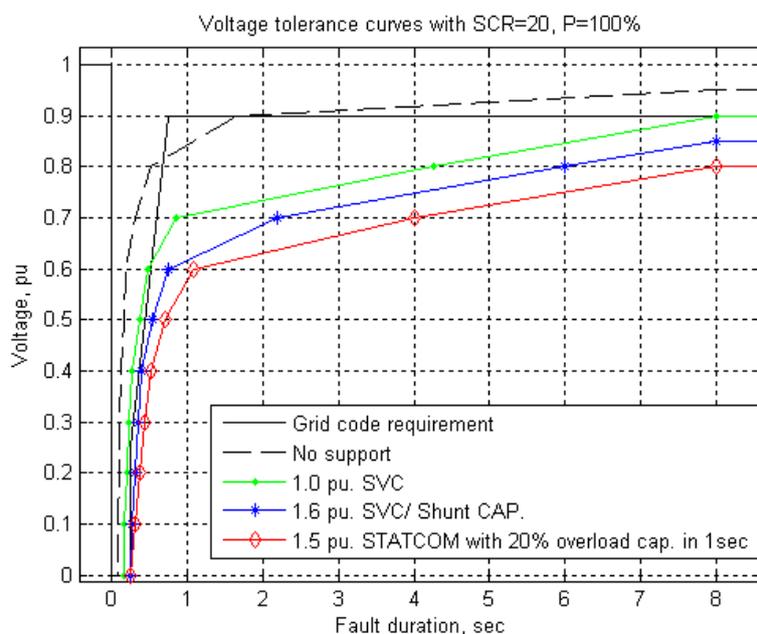
Figure 34 Tolerance curves of wind park vs. Grid Code requirement

It is obvious that in order to fulfill the Grid Code requirement on fault ride-through, it requires almost the same size for a switched shunt capacitor, an SVC, or a STATCOM. However, at less severe dips, the STATCOM can help the system withstand for longer duration.

As mentioned earlier, switched shunt capacitor is the cheapest solution but it has limited controllability which could make it difficult to meet the requirement on control of reactive power exchange with the system. SVC and STATCOM are more flexible solutions but more expensive. Detailed cost comparison of these devices is out of scope of this study. However, in general, an SVC would be cheaper than a STATCOM of the same size.

It is also important to note that if ride-through of very low voltage is not required, there may be some changes. The simulations are also implemented for the less severe dip (0.25 pu in 250 ms). The size needed to ride through this dip is 1.15 pu for an SVC and 0.8 pu for a STATCOM with 20% overload capacity in 1 sec.

In addition, the needed size depends on the installation location. The required rating for the three reactive power supporting devices at the two locations for the two ride-through requirements are summarized in Table 14.

Table 14 Required rating for different installation location and fault profile

Ride-through requirement	0 pu, 250 ms		0.25 pu, 250 ms	
Location	Location 1	Location 2	Location 1	Location 2
CAP/SVC	1.6	1.27	1.15	1.0
STATCOM	1.5	1.0	0.8	0.56

Location 1: 130 kV side of 130/400 kV onshore transformers
Location 2: 20 kV hubs on the offshore platform

Conclusions

This study has resulted in a number of conclusions which can be summarized as follows:

- The basic design of the collector system has been studied. The "radial" structure is a possible solution for the collector system of the wind park of this size, 390MW, with induction machines as generators. Transformer ratings and cable sizes have been selected.

- The reactive power consumption of the magnetizing branch of the induction generators has been compensated by a fixed capacitor bank in the design. Despite the large reactive power production of the 130 kV cables, an additional 50 MVAr reactive power is needed to achieve zero reactive power exchange with the system at full generation. Switched shunt capacitors, an SVC, a Statcom, or a combination can be used for this.

- The aggregation of the 130-turbine park into a small number of equivalent machines has been studied. It is shown that a single-machine model gives a too high error in reactive-power flow (more than 50%) to be appropriate for fault-ride-through studies. A five-machine model reduces the error to 8%. A two-machine model has been used, as a compromise to save calculation time, in the further studies.

- It is recommended that a full model or a multi-machine aggregated model is used when the fault-ride-through of a real installation is evaluated.

- Without any additional reactive power supporting devices, the system can withstand zero voltage at the point of connection for 80 ms. This is insufficient to comply with the 250 ms required in the Nordel Grid Code.

- The fault ride through can be improved by having additional capacitance available immediately after the fault.

- A combination of switched shunt capacitors of different size could be a solution for fault ride-through as well as control of reactive power or voltage.

- There is no need to switch on the capacitors very fast. It has been found that for a fault with 240 ms duration, 40 ms or 255 ms switching delay from the fault occurrence gives the same effect on system recovery. Mechanical switches may therefore be sufficient to make the capacitance available in case of a fault in the transmission system.

- There is no big difference in the required size for different reactive power supporting devices to help the wind park meet the Grid Code requirements on fault ride-through. It requires 1.6 pu for shunt capacitor bank or SVC and 1.5 pu for STATCOM with 20% overload capacity in 1 sec.

- The required size is reduced if the supporting device is installed closer to the turbines. Installing on the 20 kV side of the 20/130 kV offshore transformers requires 1.2 pu for switched shunt capacitor or SVC and 1.0 pu for STATCOM.

- If ride-through of zero voltage is not required, the size of supporting devices decreases significantly. It reduces 27% for switched shunt capacitor or SVC and 44% for STATCOM if the most severe dip required to ride through is 0.25 pu in 250 ms.

- From the study, a combination of switched shunt capacitors and an SVC could be the most economical solution for fault ride-through and reactive power control of a wind park consisting of induction generators.

Future work

Some points resulting from this work could be the basis for future studies :

- This study has been based completely on fixed-speed induction generator. A similar study could be done for for variable speed generator with DFIG and/or full power electronic converter. The control and protection of the generators will likely play an important role in such a study. An comparison of the total costs for a wind park with the different types of generators should be made.

- When evaluating the fault-ride-through of a real wind park against a real network, a more detailed model for the wind park is needed. The full model with all 130 turbines would be preferred, but the computation time could make detailed studies impossibly.One of the reasons for the long computation time is the detailed models used in EMTDC. Using a simpler model (phasors instead of time-domain) would speed up the calculations. The aggregation of wind parks into a small number of equivalent units should be studied, as well as the choice of simulation model.

- In this study only the need for reactive power has been studied. The control and protection of the reactive power source has not been studied in detail. Further study should include the control of the reactive power (switched capacitor banks, SVC, Statcom) during normal operation and during faults in the transmission system. Also the protection aspects of, especially, the capacitor banks should be studied in more detail.

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Appendix

A. Power flow from PowerWorld
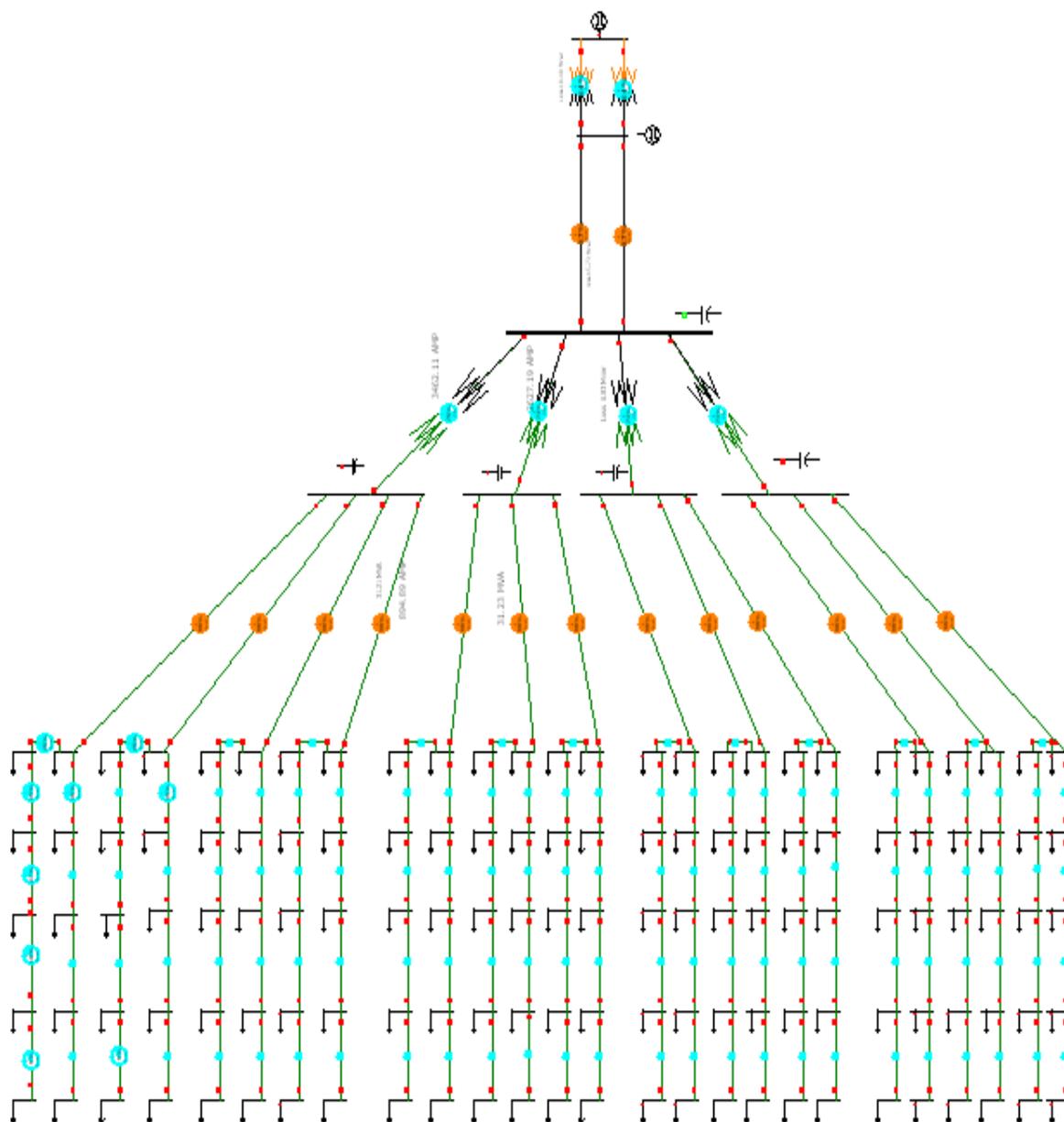
B. Wind turbine generator system in PSCad/EMTDC

3MW, 690 V Induction machine wind turbine
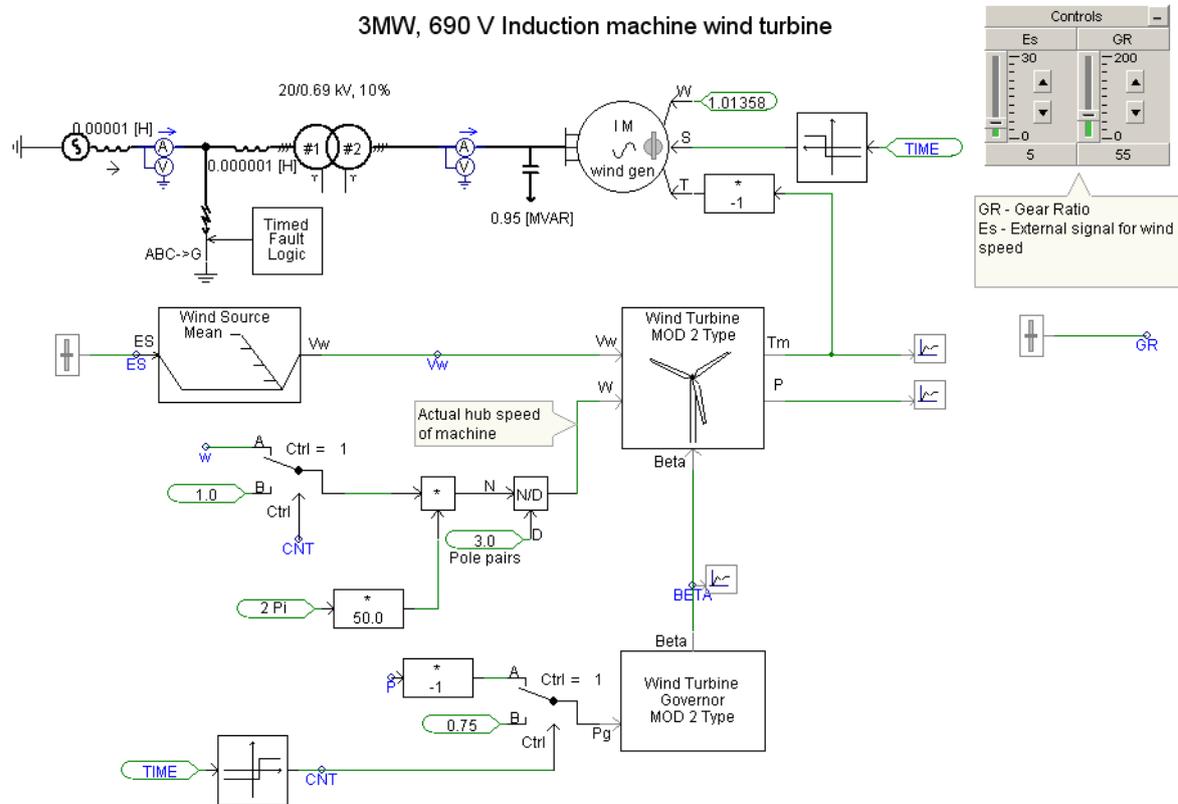
C. One feeder of 10 WTGs in 400 kV system