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Control System Design of Variable Speed Wind Turbine Based EESG for Stabilizing Distribution Plant System During Fault and Islanding

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Abstract—In this paper designing of control system of electrical excited synchronous generator based Variable Speed Wind Turbine for stabilizing electrical power distribution system during fault and temporary islanding condition is presented. The distribution plant system consists of a wind turbine based electrical excited synchronous generator, an emergency diesel engine, an induction motor and a resistive load. The distribution plant system is connected to medium voltage of utility network system. Islanding operation of the distribution system is caused by disconnecting supply power from the utility system due to short circuit on feeder of the network. In this paper the control system of wind turbine based EESG is studied. The controller is designed so that it can be operated to stabilize the distribution plant system during the fault and temporary islanding condition. The simulation study has been carried out by using PSCAD/EMTDC package program for investigating and analyzing the dynamic performance of the proposed control system. The simulation results show that the proposed control system can stabilize the distribution plant system effectively.

Index Terms— Electrical Excited Synchronous Generator, Wind Turbine Generator, Islanding Operation, Transient Stability Analysis.

I. INTRODUCTION

In order to reduce the use of fossil fuel for electricity generation and to decrease the production of pollution, the penetration of distributed generators into the network of power system have been attracted the attention of engineers all over the world. Some restrictions that affect the reliability of the grid, quality of the supplied power and safe interaction, should be carefully considered before the connection of the distributed generator to the utility power system network

Islanding is one of the most important aspect for distributed generation systems in providing a reliable connection with the utility power grid system [1]. Islanding is the condition in which a distributed generator such as wind turbine generator or PV plant continue to supply power to a local load system even though the power source from the utility power system has been disconnected [2]. Islanding operation can be caused by disturbance that makes the utility power grid to be disconnected or it can be caused by authorized people work [3]. Islanding can damage electrical devices and utility workers due to the system out of

synchronism from desired voltage and frequency references [1]. Without strict control for the balance between power production by generator and power consumption by load, the power system is going to be violated and leading to abnormal frequency and voltage [4].

Islanding topic has been reported in many papers. Most of them discuss about islanding detection or anti-islanding circuit. In [5] to [7], the wavelet transform approach for islanding detection of grid connected distributed generation is presented. [8] and [9] present fuzzy-rule and probabilistic neural network based approaches for islanding detection in distributed generation system, respectively. In this research, a control strategy of distributed generation in particularly Variable Speed Wind Turbine based Electrical Excited Synchronous Generator (VSWT-EESG) is developed for stabilizing the distribution plant system during fault and islanding conditions. The VSWT-EESG is interesting type of wind turbine generator concepts due to its advantages such as no gearbox required, no direct connection to the grid due to connection through AC-DC-AC power converter, the flux can be fully adjusted in varying operation ranges of speed, hence, the losses can be minimized, and the operating voltage (magnitude and frequency) can be controlled depending on operating voltage of grid system [10]. The controller system of VSWT-EESG is designed so that it can be operated to stabilize the distribution plant system during the fault and islanding conditions. In this paper islanded power condition is considered that occurs temporarily due to emergency diesel engine in standby on the distribution plant system.

II. DISTRIBUTION PLANT SYSTEM MODEL

In this research distribution plant system model considered in the analysis is shown in Figure 1. The distribution plant system consists of an induction motor and a resistive load which are fed at 0.4-kV from a distribution 20-kV utility network through a 1500 kVA step down transformer and from a VSWT-EESG unit. The VSWT-EESG is connected to 20 kV bus via 500 m power cable. The 20-kV utility network system is modelled by simple R-L equivalent source impedance with short circuit level at 100 MVA with R/X ratio of 10%. The induction motor is induction machine of squirrel cage type rated at 800 kW. Resistive load is 150 kW. An emergency diesel engine feeds the distribution plant at 0.4 kV. A 100 kVar capacitor bank is

installed on the 0.4 kV network. The capacitor bank is used to compensate the reactive power consumption by the distribution plant system.

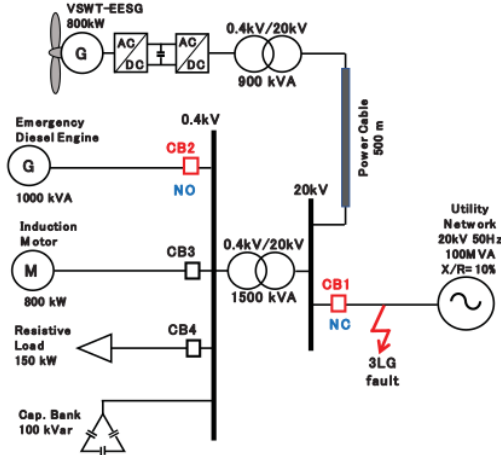


Figure 1. Distribution power system model

A. Emergency Diesel Engine Model

The diesel engine in this paper is considered as emergency generator rated at 1000 kVA. The generator, excitation and governor models are performed by the standard models provided in the master library of the PSCAD/EMTDC [11]. The generator model is standard synchronous machine. Table I shows the parameters of the emergency diesel generator. Automatic Voltage Regulator (AVR) is based on an IEEE type SCRX solid state exciter. Figure 2 shows the AVR model. The AVR system maintains terminal voltage output of generator stator (V_t) at reference voltage (V_{ref}) by controlling the field voltage (E_f) of the rotor. As engine and governor system models, the standard models of the Internal Combustion (IC) engine presented in machines library of PSCAD/EMTDC is used.

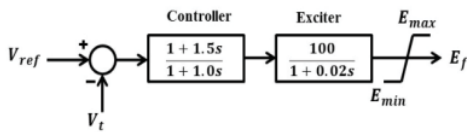


Figure 2. AVR model

TABLE I. GENERATOR PARAMETERS OF DIESEL ENGINE

Rated Power	1000 kVA
Voltage	0.4 kV
Frequency	50 Hz
Inertia Constant	3.0 s
Armature Resistance	0.005 pu
Stator Leakage Inductance	0.103 pu
d-axis Synchronous Reactance	2.11 pu
d-axis Transient Reactance	0.35 pu
d-axis Subtransient Reactance	0.21 pu
q-axis Synchronous Reactance	2.02 pu
q-axis Subtransient Reactance	0.21 pu
d-axis Transient Time Constant	8.6 s
d-axis Subtransient Time Constant	0.003 s
q-axis Subtransient Time Constant	0.002 s

B. Load Model

Load model of the distribution plant is represented by an 800 kW induction motor and 150 kW resistive load. Table II shows the parameters of the induction motor.

TABLE II. INDUCTION MOTOR PARAMETER

Rated Power	800 kW
Voltage	0.4 kV
Frequency	50 Hz
Angular Moment of Inertia	1.3 s
Mechanical damping	0.005 pu
Stator Resistance	0.043 pu
Rotor Resistance	0.04 pu
Magnetizing Inductance	4.0 pu
Stator Leakage Inductance	0.06 pu
Rotor Leakage Inductance	0.06 pu

TABLE III. GENERATOR PARAMETER OF VSWT-EESG

Rated Power	800 kW
Voltage	0.4 kV
Frequency	20 Hz
Inertia Constant	2.0 s
Stator winding Resistance	0.006 pu
Stator Leakage Inductance	0.18 pu
d-axis Synchronous Reactance	1.305 pu
d-axis Transient Reactance	0.296 pu
d-axis Subtransient Reactance	0.252 pu
q-axis Synchronous Reactance	0.474 pu
q-axis Subtransient Reactance	0.243 pu
d-axis Transient Time Constant	4.49 s
d-axis Subtransient Time Constant	0.0681 s
q-axis Subtransient Time Constant	0.0513 s

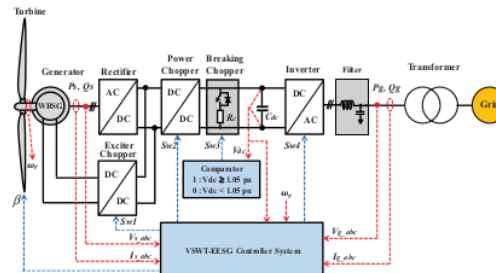


Figure 3. VSWT-EESG and control system Model

III. PROPOSED CONTROL OF VSWT-EESG

Block diagram of VSWT-EESG model is shown in Figure 3. The model of VSWT-EESG consists of wind turbine, a Wound Rotor Synchronous Generator (WRSR), a rectifier, an exciter chopper, a power chopper, a breaking chopper, an inverter, a harmonic filter, step up transformer and the EESG based wind turbine controller system. Table III shows the parameter of the WRSR used in the simulation. The WRSR model used in this paper is standard model available on the PSCAD/EMTDC library, where, the generator losses are not considered. The controller system of VSWT-EESG controls pitch blade angle (β), switching control of exciter chopper ($Sw1$), switching control of power chopper ($Sw2$) and switching control of the inverter ($Sw4$). The breaking

chopper's switching control (Sw_3) is controlled by DC-link protection controller.

The rotor of the WRSG is directly driven by hub of wind turbine blade without gearbox. Stator and rotor windings of the WRSG are connected to the rectifier and the exciter chopper, respectively. The rectifier converts three phase AC voltage from WRSG to DC voltage by using six diodes rectifier circuit. The exciter chopper is used to control field voltage of rotor winding of the WRSG.

The DC-link circuit is equipped by a power chopper. The power chopper controls the active power from the generator to DC link-circuit. Furthermore, the breaking chopper is also embedded in the DC-link circuit. The breaking chopper protects the DC-Link circuit from damage when over voltage occurs on the circuit. Over voltage on the DC-link circuit can appear if a disturbance such as voltage dip due to short circuit happening on the grid system. The voltage dip can lead the power output of inverter decreases, hence, there is an imbalance of power between the generator and the inverter output. The breaking chopper dissipates the active power from the generator in breaking resistance (R_c). When the DC-link voltage exceeds the allowable voltage limit (1.05 pu) then the breaking chopper is only activated.

The inverter system is IGBT's two level converter which is connected to the grid. The inverter converts the DC voltage to the three phase AC voltage depending on operating voltage and frequency of the power system grid. The LC filter is located between the inverter and step up transformer for filtering current and voltage harmonics produced by the inverter.

A. Wind Turbine and Drive Train Models

The wind turbine power can be expressed as follows [12]:

$$P_w = 0.5\rho\pi R^2 V_w^3 C_p(\lambda, \beta) \quad (1)$$

where

- P_w : wind power (W)
- ρ : air density (Kg/m³),
- R : radius of rotor blade (m),
- V_w : wind speed (m/s)
- C_p : the power coefficient.
- λ : tip speed ratio
- β : pitch angle (deg)

The wind turbine characteristics can be calculated as follows [12]:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3\beta - c_4 \right) e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \quad (2)$$

with

$$\lambda = \frac{\omega_r R}{V_w} \quad (3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda - 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

where

- c_1 to c_6 : coefficients of wind turbine [13]
- : $c_1=0.5176$; $c_2=116$; $c_3=0.4$; $c_4=5$; $c_5=21$; $c_6=0.0068$
- ω_r : turbine rotational speed (rad/sec).

The wind turbine drive train model considered in this paper is modeled in single rotating mass model which it expressed as follows:

$$T_m - T_e = \frac{1}{J_t} \frac{d\omega_r}{dt} \quad (5)$$

where

- T_m : mechanical torque
- T_e : electrical torque
- J_t : total moment of inertia of the turbine and generator

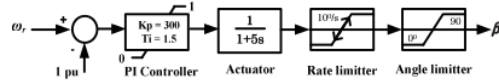


Figure 4. Pitch blade control system model

B. Pitch Blade Controller

Pitch blade control system plays a very important role in keeping the wind turbine speed not exceeding the maximum speed limit when the wind blows very high. If the pitch controller doesn't work properly, then the wind turbine rotor will rotate very fast that it can cause the serious damage on wind turbine generator unit. The pitch blade control system regulates the rotational speed (ω_r) of wind turbine rotor not to exceed the maximum speed limit (1.0 pu). The pitch blade controller manages attack angle of the pitch blade (β) to reduce speed of the rotor blade. Figure 4 shows detail of the pitch blade control system model. The control system model consists of a PI controller, pitch actuator and pitch rate limiter.

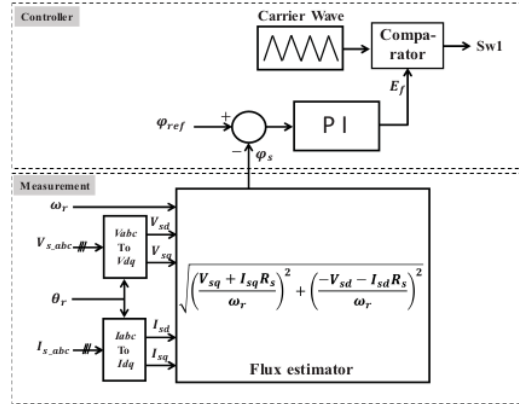


Figure 5. Exciter converter controller model

C. Exciter Chopper controller

Figure 5 shows the exciter chopper controller model. The exciter chopper controller is used to control field voltage (E_f) fed to rotor winding of EESG. The field voltage is obtained by controlling the flux of stator winding (ϕ_s), where the stator flux reference (ϕ_{ref}) is set to constant value at 1.0 pu. The flux is controlled in order to minimize losses in different operating ranges of VSWT-EESG. The three phase voltage and current of stator winding of the WRSG (V_{s_abc} and I_{s_abc}) are converted to the dq-axis form by using park transformation, where θ_r is phase angle obtained from the rotor speed. The flux of stator winding can be estimated by using flux equation as written as follows:

$$\phi_s = \sqrt{\left(\frac{V_{sq} + I_{sq}R_s}{\omega_r}\right)^2 + \left(\frac{-V_{sd} - I_{sd}R_s}{\omega_r}\right)^2} \quad (6)$$

where

V_{sd} and V_{sq} : stator voltage of the WRSG in the dq-axis form
 I_{sd} and I_{sq} : stator current of the WRSG in the dq-axis form
 R_s : stator winding resistance

D. Power Chopper controller

Figure 6 shows a block diagram of the power chopper controller model. The power chopper controls the output current of the rectifier (I_{dc}) and power output of WRSG (P_s). The controller generates the gate signal (by acting decrease and increase) depending on the PWM duty cycle (D). The duty cycle is obtained through a PI controller. The Maximum Power Point Tracking (MPPT) calculate the power reference (P_{ref}) based on the rotational speed of wind turbine as expressed in Equation (7) [14]:

$$P_{mppt} = 0.5\rho\pi R^2 \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 C_{p_{opt}} \quad (7)$$

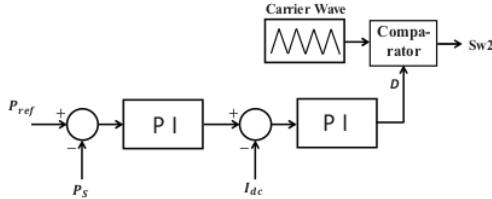


Figure 6. Power chopper controller model

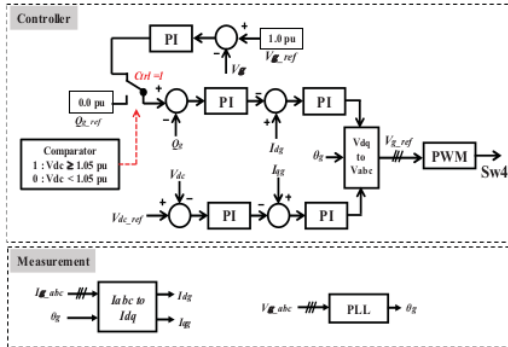


Figure 7. Inverter controller model

E. Inverter controller

The inverter controller keeps the voltage on the DC-link circuit constant so that active power from WRSG can be supplied to the utility grid system. In addition, the inverter controller can regulate supply of the reactive power to the distribution network if necessary.

In Figure 7 the model of inverter controller is depicted. Three phase of grid current (I_{g_abc}) and three phase of grid voltage (V_{g_abc}) are detected from grid side output of LC filter. The phase angel of the grid voltage (θ_g) is obtained through Phase Locked Loop (PLL) controller [11]. By using

the Park Transformation, the grid current (I_{g_abc}) is transformed into the dq-axis form, then becomes I_{dq} and I_{qd} , respectively. By this way, supply of active and reactive powers to the distribution network can be controlled separately. The d-axis current of the grid (I_{dg}) can control the reactive power. On the other hand, the q-axis grid current (I_{qg}) can control the voltage of DC-link (V_{dc}) to remain constant at reference voltage (V_{dc_ref}), hence the active power output of the generator can be supplied to the distribution network.

In normal condition, the inverter is operated at unity power factor, and thus, in this mode the reactive power reference (Q_{ref}) is set to zero. During fault and islanding conditions the fault mode operation is activated. It should be noted that there is no islanding detector in the controller system. The fault mode operation would be triggered when the voltage of DC-link circuit exceeds the maximum limit of the allowable voltage (1.05pu). During fault mode operation, the output voltage of inverter remains constant by changing the reactive power output reference.

IV. SIMULATION RESULTS

In this paper the distribution plant system shown in Figure 1 is analyzed. In normal condition the distribution plant system is fed from utility network system and the VSWT-EESG. The emergency diesel engine is in standby, providing no power to the plant. The VSWT-EESG is operated in unity power factor operation and the wind speed hit the wind turbine is kept at 10 m/sec by assumption that no wind speed change at short interval of the time. The induction motor is operated at 0.83 pu of load torque.

A three lines to ground fault (3LG) is happened at the feeder of utility network system near the terminal bus of the 20kV/0.4kV 1500 kVA transformer. At 0.1 sec the fault is occurred and then the circuit breaker CB1 is opened at 0.2 sec to isolate the distribution plant system from the disturbance and the utility network system. After CB1 is opened, the emergency diesel engine is started to supply necessary active and reactive powers to the plant system. However, the CB2 would be closed when the emergency diesel engine reaches idle condition, 0.5 sec late after CB1 is opened. This condition caused the distribution plant system to be in islanding operation.

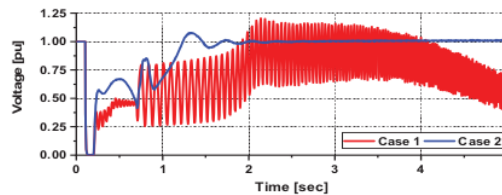


Figure 8. Voltage performance at 0.4 kV of bus terminal volatge

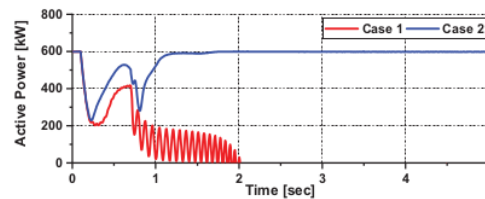


Figure 9. Active power of VSWT-EESG

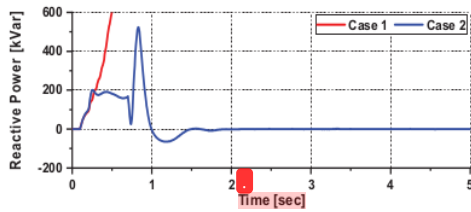


Figure 10. Reactive power of VSWT-EESG

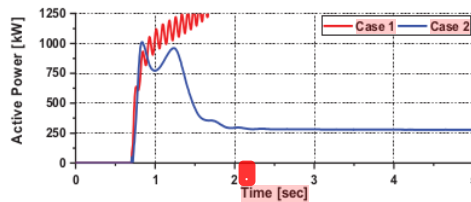


Figure 11. Active power of diesel engine

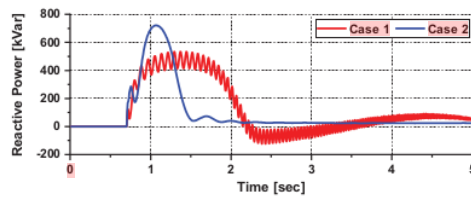


Figure 12. Reactive power of diesel engine

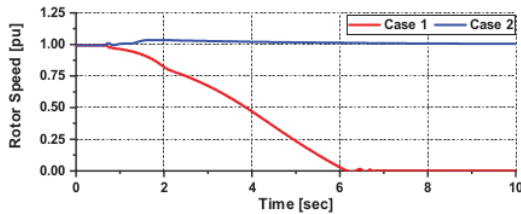


Figure 13. Rotor speed of diesel engine

The proposed control of VSWT-EESG for stabilizing the distribution plant system during fault and islanding has been investigated by considering two cases in the simulation study. In Case 1, the control system of VSWT-EESG is kept in normal operation. In Case 2, the fault mode operation of VSWT-EESG is considered. Figure 8 shows voltage performance at 0.4 kV bus terminal of the distribution plant system. Active and reactive powers performances of the VSWT-EESG are depicted in Figures 9 and 10, respectively. Figures 11 and 12 depict performances of active and reactive

powers output of the emergency diesel engine, respectively. Finally, Figure 13 shows response of rotor speed of diesel engine generator. From the simulation results it is clear that the distribution plant system become unstable in Case 1. Otherwise, it is seen the proposed control of VSWT-EESG can stabilize the distribution plant system during 3LG fault and temporary islanding condition as presented in Case 2.

V. CONCLUSION

A control system design of Variable Speed Wind Turbine based Electrical Excited Synchronous Generator (VSWT-EESG) for stabilizing the distribution plant system during fault and islanding condition has been presented. In can be concluded that the proposed control method of the VSWT-EESG can control the terminal voltage of the distribution plant system to return back to initial condition. Moreover, both the active and reactive power to the distribution plant system can be recovered effectively during and after fault and temporary islanding condition.

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