Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

10th International Conference
on Electrical Engineering
ICEENG 2016

Impact of SVC on Voltage Stability of HWF Wind Farm during Grid Disturbance

By

Ahmed Rashad[1], Salah Kamel[2], Francisco Jurado[3]

Abstract:

The continuous increase in the pollution level and fuel price lead to increase the using of renewable energy sources especially wind energy. Due to the increase in wind energy penetration into electrical grid, installing wind farms faces many challenges. Continuity of wind farms connection to grid or at least reconnected after clearance of grid faults is important challenge. To overcome these challenges Flexible AC transmission systems (FACTS) elements are used as auxiliary equipment. This paper studies the impact of static var compensator (SVC) as one of FACTS family members on voltage stability of hybrid wind farm (HWF) during some grid disturbance such as over voltage, voltage sage, single to ground fault and three phase faults. This hybrid wind farm is consisting of an equal number of Squirrel Cage Induction Generator (SCIG) and Double Fed Induction Generator (DFIG). With this combination, the main benefits of SCIG and DFIG are collected. Where, SCIG is considered cheap with great effect on system stability especially when it operates without shunt compensator while DFIG can be operated with more stability contributes in the stability of interconnected grid. But DFIG is considered very expensive comparing with SCIG. The current paper presents a comprehensive comparison of recent hybrid wind farm with and without SVC during different types of grid disturbance. All test cases are carried out using MATLAB SIMULINK program.

Keywords:
SCIG, DFIG, Hybrid wind farm and SVC

---

* 1 University of Jaén, 23700 EPS Linares, Jaén, Spain arashad@ujaen.es,& ahmedmmrashadar@gmail.com
2 Department of Electrical Engineering, Faculty of Engineering, Aswan University, 81542 Aswan, Egypt
3 Department of Electrical Engineering, University of Jaén, 23700 EPS Linares, Jaén, Spain

1. Introduction:

The importance of renewable energy was appeared In the middle of past century as alternative source to traditional methods of electrical generation system. Most of European countries increased their researches towards renewable energy and because the wind in these countries features with high speed while they suffer from shortage of solar energy so that they accelerated their researches in wind energy field. As result of these researches, these countries expanded in build wind farms. The increase in wind energy penetration into the grid forced the power system operators to make rules for connecting wind power plant to the grid.

The researches turned towards study the impact of wind energy penetration into electrical grid in steady stat conditions and special in emergency conditions. This impact is due to the type of generators that is used to convert the stored energy in wind into electrical energy. In the begging of installing wind farm SCIG was the first type that had been used for this propos then DFIG represents the second generation of induction used in wind farms. With the increase in wind energy penetration into the grid the need to improve the impact of these types became an important issue representing a wide field for researchers.

DFIG wind turbines are the modern type but they are more expensive than SCIG wind turbines. DFIG wind turbines can give a voltage support to grid during fault events but they still suffer from dropping in its output power to zero without disconnecting the wind farm from the grid while SCIG wind turbines suffer from disconnection of the wind farm from the grid during fault events. Many researches have studied the dynamic behavior of SCIG or DFIG during LVRT condition [1], [2], [3] and [4]. To overcome these challenges Flexible AC transmission systems (FACTS) elements are used as auxiliary equipment. Some researchers treated this point in their researches by using Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) such as [5] and [6]. Other researchers used STATCOM to enhancement the operation of wind farm based on DFIG wind turbines such as in [7] and [8]. Using FACTS with wind farms to meet these challenges will cause an additional cost to wind farm installation. Also all these reaches used FACTS to enhancement the performance of wind farms based only one type induction generators whatever SCIG or DFIG.

This paper aims to represent a new method of wind farm installation that can fulfill challenges which face wind farms interconnected grid and in the same time decrease the cost of wind farm installation as much as possible. To achieve this aim the paper proposed combination between SCIG wind turbines and DFIG wind turbines in the same wind farm. Also in this paper the performance of this hybrid wind farm (with and without SVC) grid voltage disturbance such as overvoltage, voltage sag, single line to ground fault and three phase fault according to the German grid operator – E.ON [9] is analyzed.

2. Description of Studied System:

The studied system consists of a wind farm connected to 120 kV grid via 25 kV, 30 km transmission line. The studied wind farm consists of six 1.5 MW generators. The HWF was based on 50% SCIG and 50% DFIG (3 SCIG and 3 DFIG). The SVC is connected in shunt with the HWF at the point of common connection (PCC). The faults occur at the end of transmission line. The single line diagram of the studied system is shown in Fig. 1.

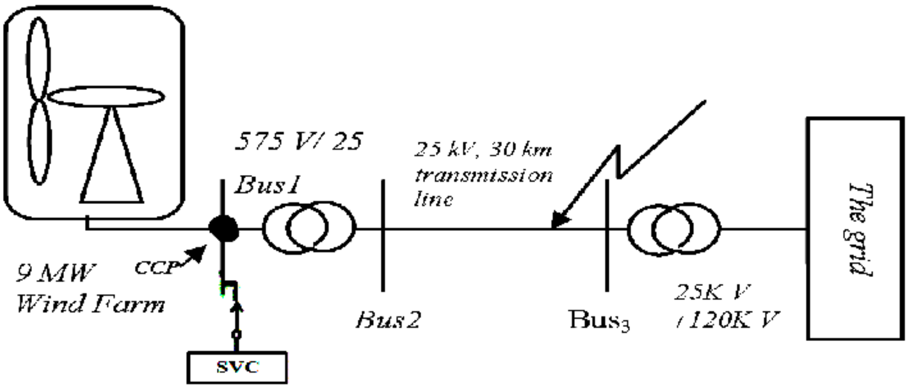

Figure (1): *Single line diagram of studied wind farm.*

2.1. parameters of studied system:

The parameters of studied system such as characteristic of SCIG wind turbine (rating, base wind speed,…) , characteristic of DFIG wind turbine(rating, base wind speed,…), parameters of AC/DC/AC converter and parameters of protection system are given appendix (A) [10].

2.2. Squirrel Cage Induction Generator (SCIG)

Fig.2. shows a single line diagram of SCIG wind turbine where the wind turbine rotor is coupled to the generator through a gear box while the stator is connected to the grid through a two winding transformer. A capacitor bank connected across the stator terminals of a 3-phase induction generator in order to supply the reactive power to the induction generator for self-excitation process [10].

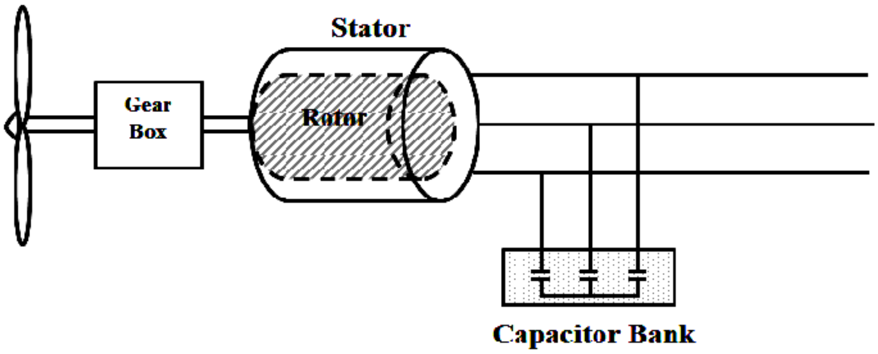

***Figure (2):** Single line diagram of SCIG wind turbine.*

The next equation is used for mathematical modeling of Squirrel Cage Induction Generator (SCIG) [11]

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_s & 0 & pL_{ms} & 0 \\ 0 & r_s + pL_s & 0 & pL_{ms} \\ pL_{ms} & -\omega_r L_{ms} & r'_r + pL'_r & -\omega_r L'_r \\ \omega_r L_{ms} & pL_{ms} & \omega_r L'_r & r'_r + pL'_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} \tag{1}$$

2.3. Doubly Fed Induction Generator (DFIG)

Fig.3. shows a DFIG connected to the grid. The AC/DC/AC converter is divided into two components: the rotor side converter C_{rotor} and the grid-side converter C_{grid}. C_{grid} and C_{rotor} are Voltage-Sourced Converters that use forced-commutated power electronic devices (IGBT s) to synthesize an AC voltage from a DC voltage source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor L is used to connect to the grid [10].

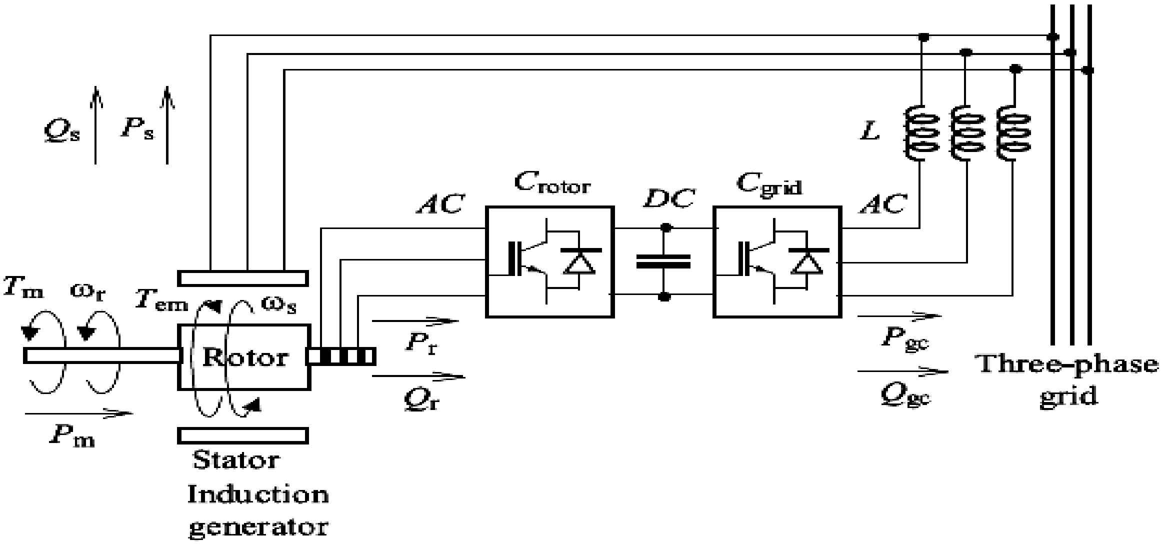

***Figure (3):** Single line diagram of DFIG wind turbine*

The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The control system generates the pitch angle command and the voltage command signals for C_{grid} and C_{rotor} in order to control the power of the wind turbine, the DC bus voltage (Vdc) and the voltage at the grid terminals. The mathematical modeling of DFIG is given by (2) [12]:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} r_s + pL_s & 0 & pL_{ms} con\theta_r & -pL_{ms}\sin\theta_r \\ 0 & r_s + pL & pL_{ms}\sin\theta_r & pL_{ms}\cos\theta_r \\ pL_{ms}\cos\theta_r & pL_{ms}\sin\theta_r & r_r' + pL_r' & 0 \\ -pL_{ms}\sin\theta_r & pL_{ms}\sin\theta_r & 0 & r_r' + pL' \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr}' \\ i_{dr}' \end{bmatrix} \qquad (2)$$

2.4 static var compensator (SVC):

The SVC is the most popular member of the FACTS family. It is a shunt device used power electronic devices to regulate the voltage at its terminal and hence regulate the voltage of the grid. SVC regulates the voltage by controlling the amount of reactive power which can be injected or absorbed according to the grid voltage condition [10].

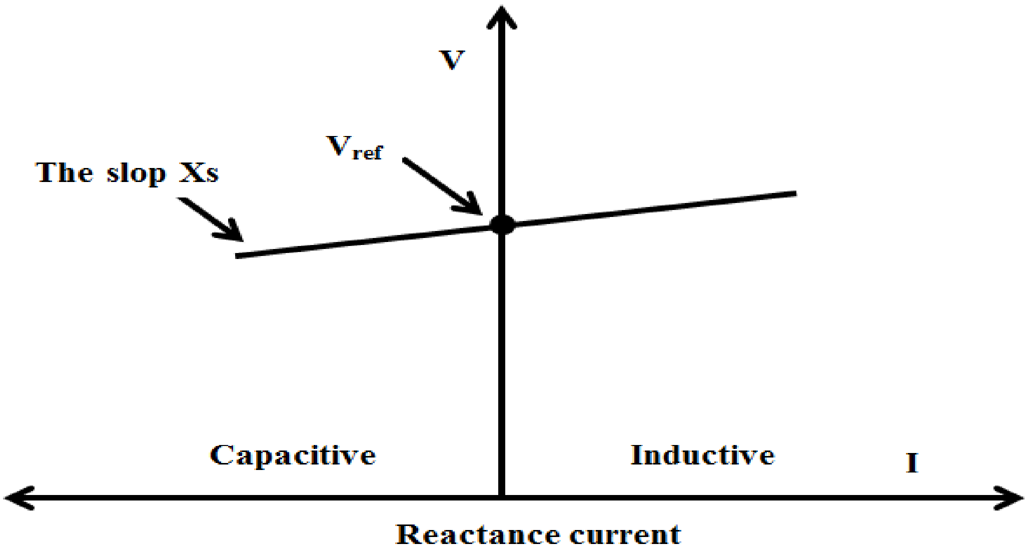

***Figure (4):** SVC V-I characteristic*

Fig.4 shows V-I characteristic of SVC where V_{ref} is the reference voltage, Xs is slope or droop reactance, I is reactive current. When system voltage is low, the SVC injects reactive power to the system (SVC capacitive) while when system voltage is high, it absorbs reactive power (SVC inductive).

3. Voltage Stability Index

The Voltage Stability Indices (VSI) are taken as an instrument that will measure the voltage stability of the studied power system [15]. The paper used a VSI formulation proposed in [16] order to that HWF without SSSC can give the same performance even better than wind farm based on DFIG wind turbines whatever it is associated with SVC. The next equation represents principle of VSI used in this paper [11]:

$$|V_i|^4 - 4|V_i|^2\left(P_j R + Q_j X\right)VSI - 4\left[\left(P_j X - Q_j R\right)VSI\right]^2 \geq 0 \qquad (3)$$

According to (3), VSI will have the following characteristics:

a) When VSI is greater than 1 when the transmission line is within its power transfer limit;
b) When VSI is equal to 1 when the transmission line is reaching maximum power transfer capability;
c) When VSI is less than 1, maximum power transfer limit is violated, and voltage

becomes unstable.

The equation (3) has been modified to the next equation [23]:

$$VSI = \frac{|V_i|^2 \sqrt{\left[\left(P_i - |I|^2 R\right)^2 + \left(Q_i - |I|^2 X\right)^2\right]\left(R^2 + X^2\right)}}{2\left(P_i X - Q_i R\right)^2} - \frac{|V_i|^2\left(\left(P_i - |I|^2 R\right)R + \left(Q_i - |I|^2 X\right)X\right)}{2\left(P_i X - Q_i R\right)^2} \tag{4}$$

Equation (18) is implemented in Matlab/Simulink.

4. Simulation Results

The simulation is performed in two case; the first case was studding the performance of HWF wind farm during over voltage, voltage sage, single to ground fault and three phase faults occurred at the end of transmission line and continued to 150 mse according to the German grid operator – E.ON. HWF operates wind speed equal to 8 m/s. All measurements were taken at bus 1 which presents the point of common connection.

4.1. The first case; overvoltage case

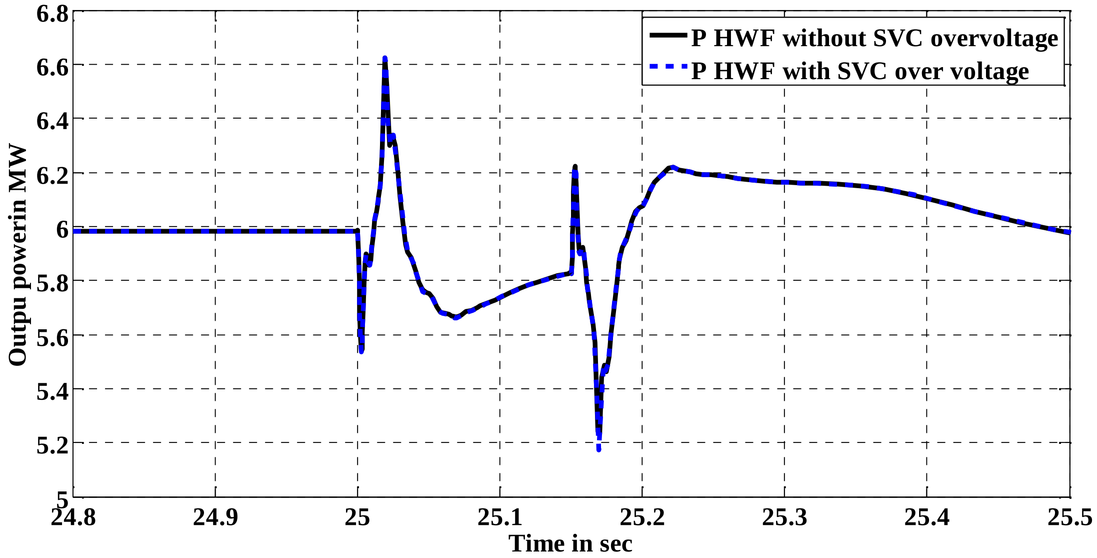

Figure (5): *Output power of HWF (with and without SVC) during overvoltage condition*

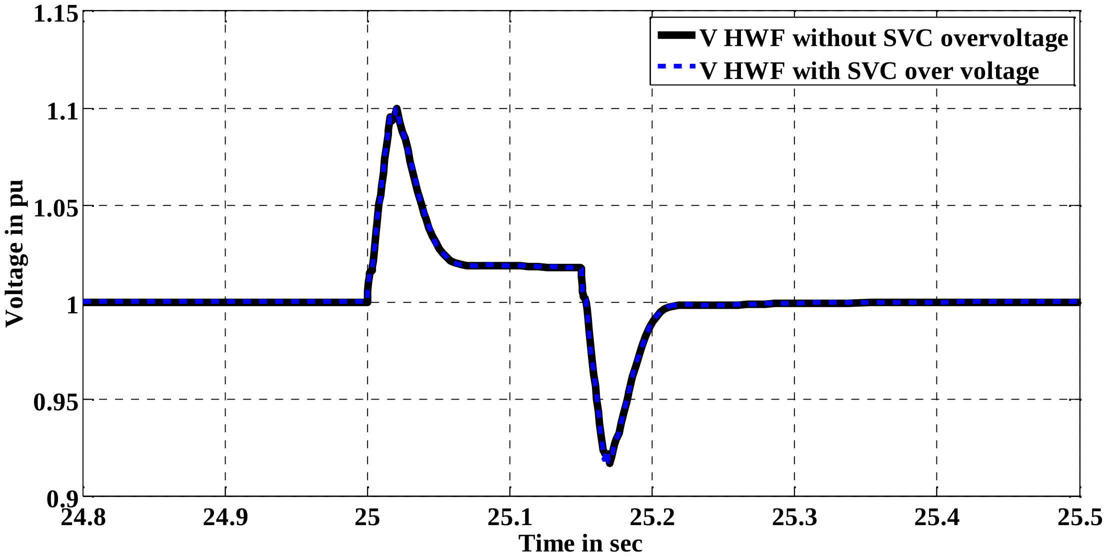

Figure (6): *Voltage of HWF (with and without SVC) during overvoltage condition*

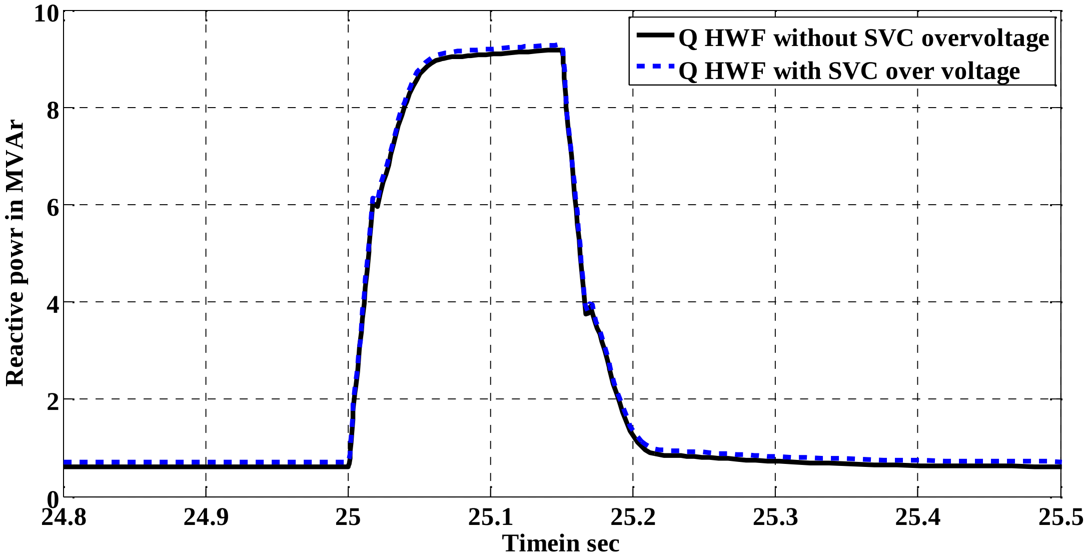

Figure (7): *Reactive power of HWF (with and without SVC) during overvoltage condition*

From Fig.5, 6 and 7 it can be observed that the curves of voltage, output and reactive power in HWF with SVC and HWF without SVC are almost indicated. So that it can be said that the SVC has unremarkable effect on performance of HWF during overvoltage condition. The voltage stability of the system is examined using voltage stability index as shown in Fig. 8.

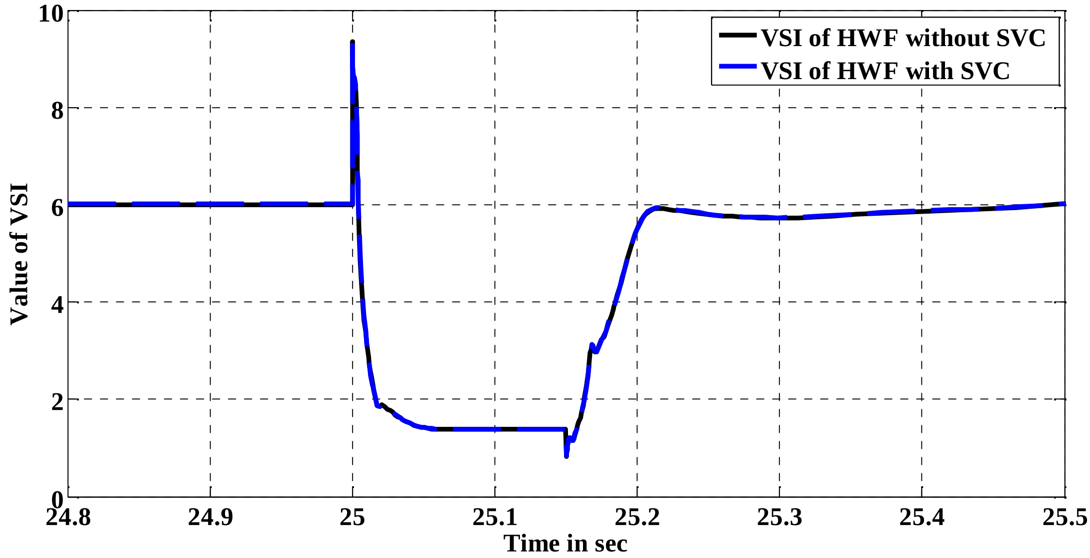

Figure (8): *VSI of HWF (with and without SVC) during overvoltage condition*

Fig .8 shows that in both cases HWF with or without SVC the system is great than 1 which means the system is stable during simulation time. Also shows that the performance of HWF without SVC is the same as HWF with SVC

4.2. The second case; voltage sag case

In this case the grid voltage is dropped to 0.75 pu from time equal to 25 sec to time equal to 25.150 sec from the simulation time.

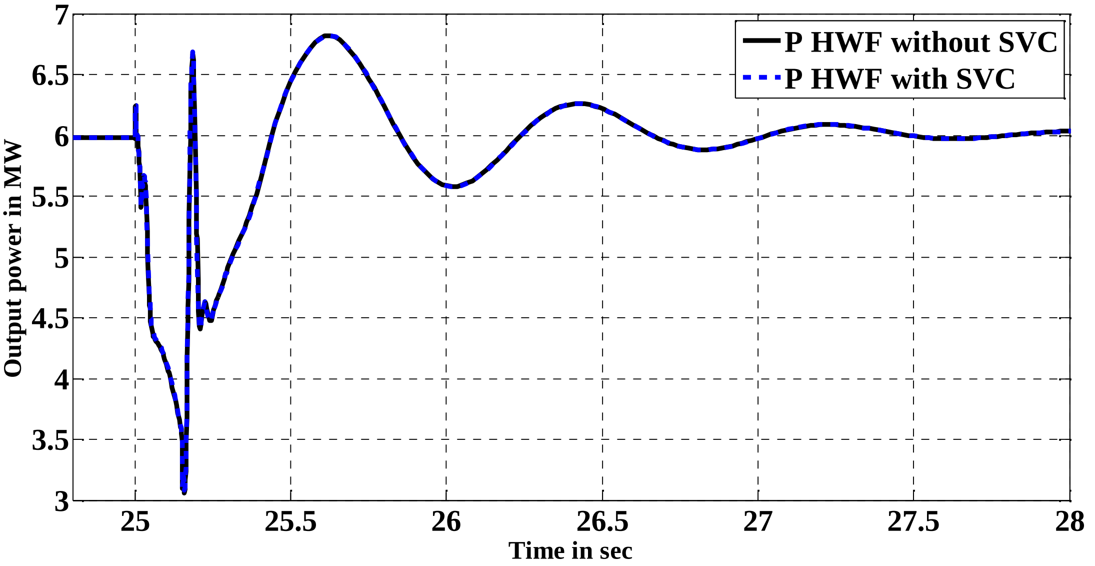

Figure (9): *Output power of HWF (with and without SVC) during voltage sag condition*

From Fig.9, 10 and 11 it can be observed that the HWF has the same performance whatever it associated with SVC or not. So that it can be said that the SVC has unremarkable effect on performance of HWF during voltage sag condition. The voltage stability of the system is examined using voltage stability index as shown in Fig. 12.

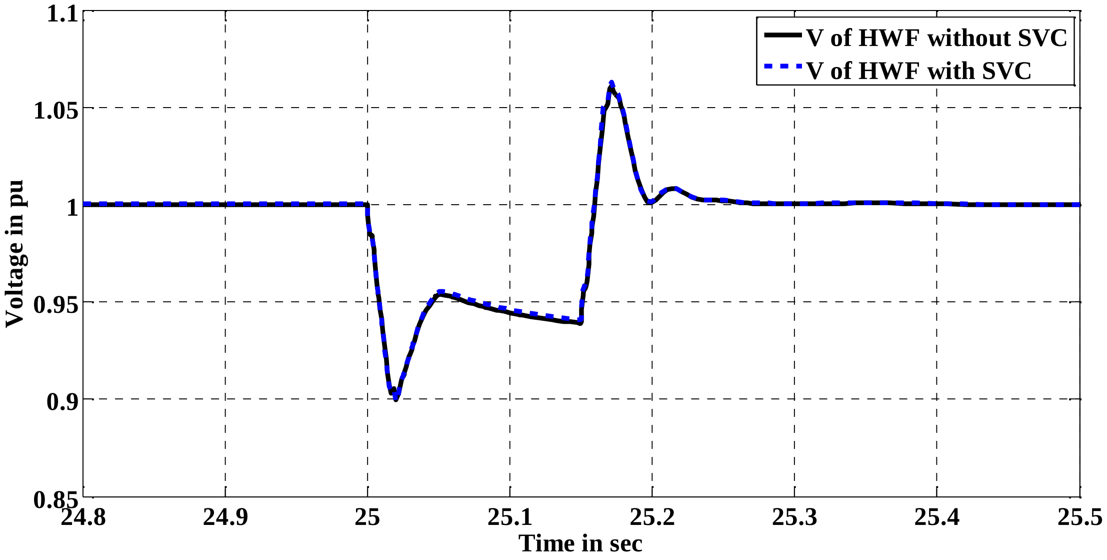

Figure (10): *Voltage of HWF (with and without SVC) during voltage sag condition*

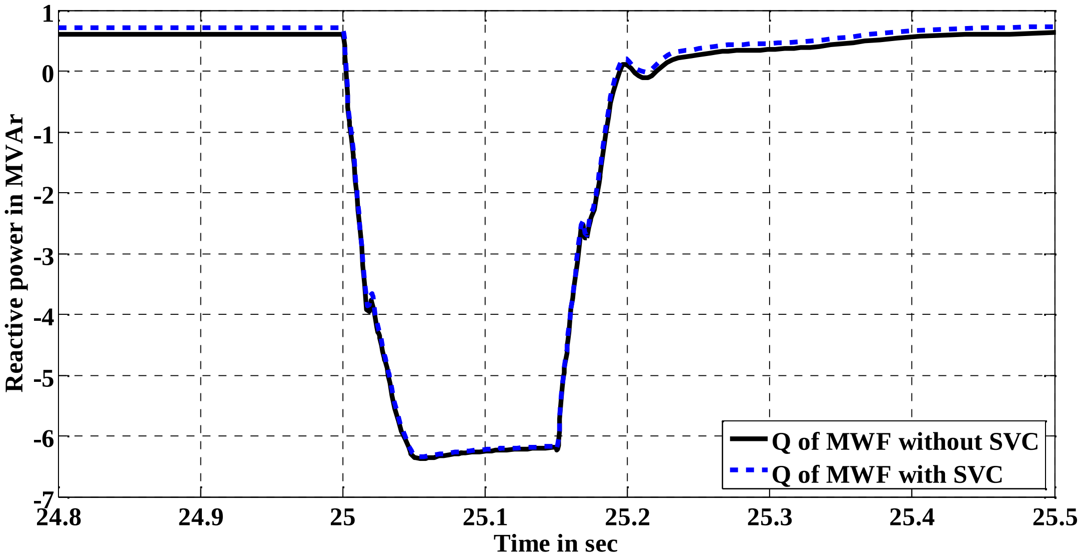

Figure (11): *Reactive power of HWF (with and without SVC) during voltage sag condition*

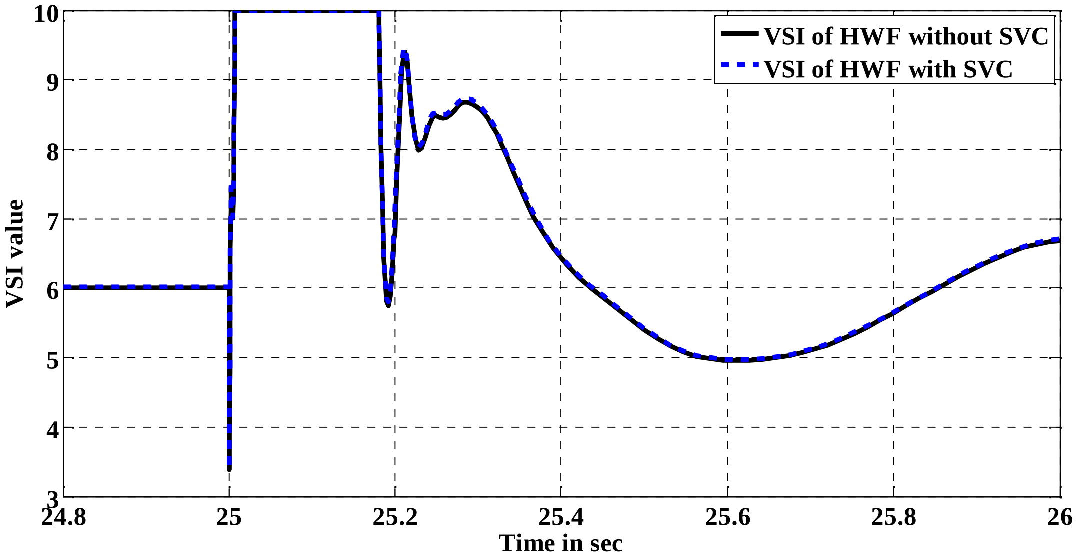

***Figure (12):** VSI of HWF (with and without SVC) during voltage sag condition*

Fig .12 shows that in both cases HWF with or without SVC the system is great than 1 which means the system is stable during simulation time. Also shows that the performance of HWF without SVC is the same as HWF with SVC.

4.3. The thrid case; single line to ground fault

In this case the performance of HWF with and without SVC during single line to ground fault accrued at the end of transmission line at time equal to 25 sec to time equal to 25.150 sec from the simulation time.

From Fig.13, 14 and 15, it can be observed that the HWF has the same performance whatever it associated with SVC or not. So that it can be said that the SVC has unremarkable effect on performance of HWF during voltage sag condition. The voltage stability of the system is examined using voltage stability index as shown in Fig. 16.

Fig .16 shows that in both cases HWF with or without SVC the system is great than 1 which means the system is stable during simulation time. Also shows that the performance of HWF without SVC is the same as HWF with SVC.

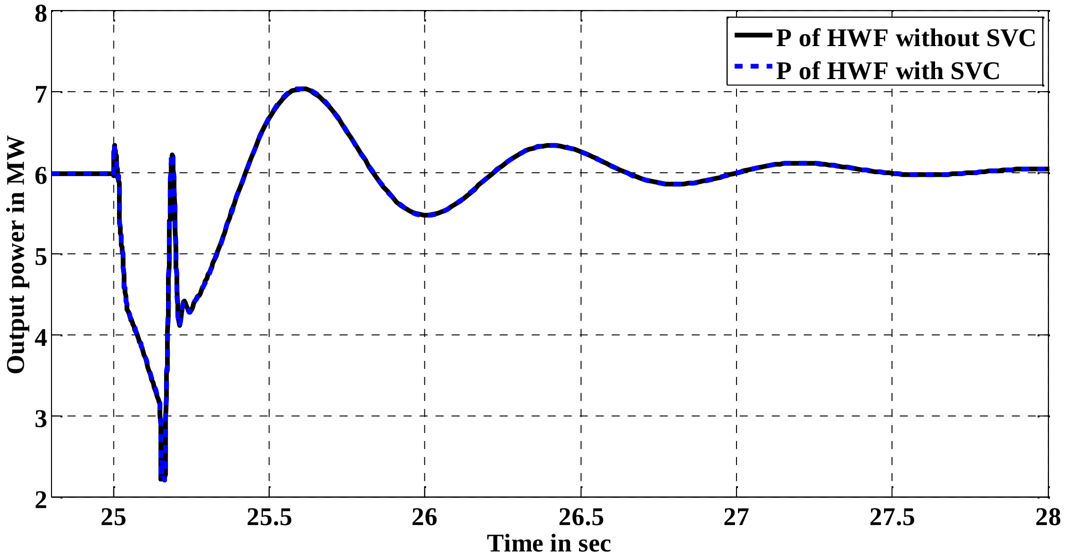

Figure (13): *Output power of HWF (with and without SVC) during single line to ground fault condition*

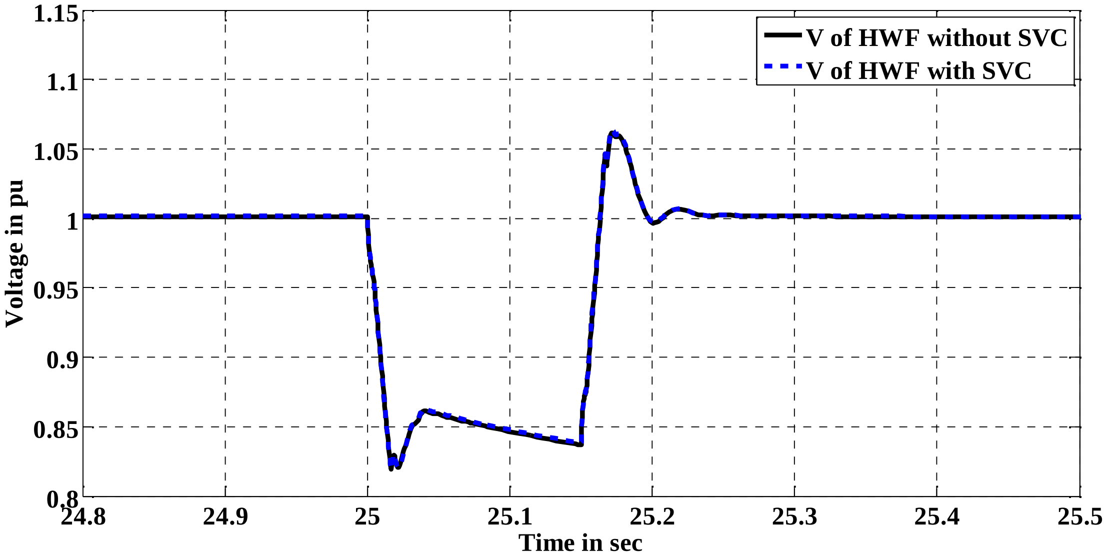

Figure (14): *Voltage of HWF (with and without SVC) during single line to ground fault condition*

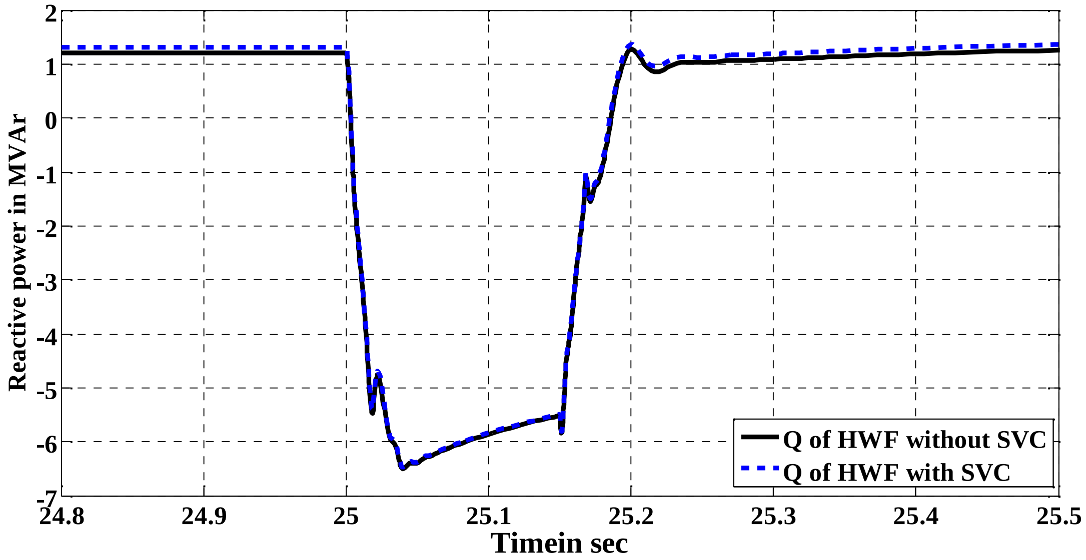

Figure (15): *Reactive power of HWF (with and without SVC) during single line to ground fault condition*

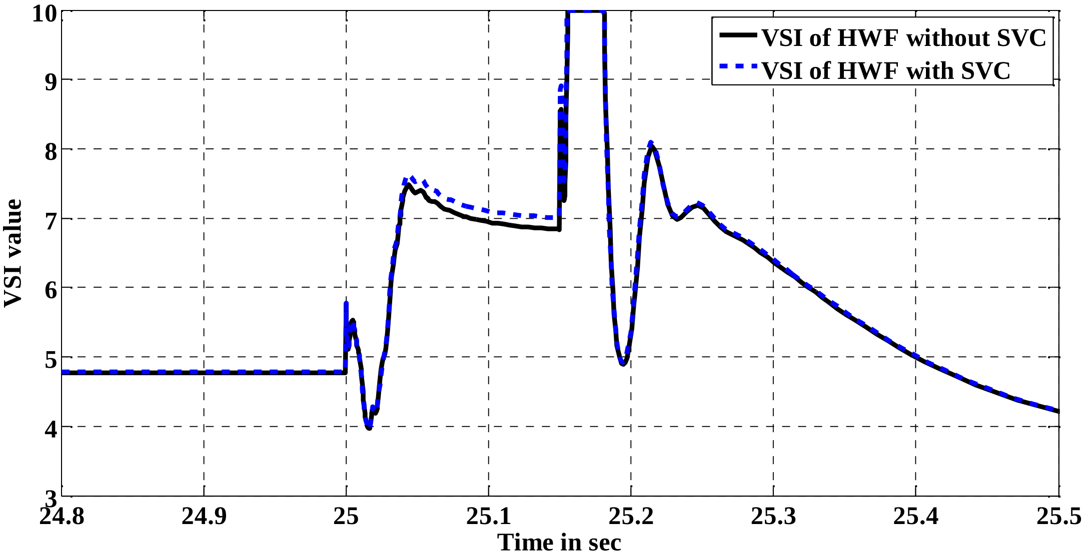

Figure (16): *VSI of HWF (with and without SVC) during single line to ground fault condition*

4.4. The fourth case; three phase fault

In this case, the performance of HWF with and without SVC during three phase fault accrued at the end of transmission line at time equal to 25 sec to time equal to 25.150 sec from the simulation time. From Fig.17, 18 and 19, it can be observed that the parameters (P, Q and V) of the HWF have almost the same values whatever the HWF associated with SVC or not. So that it can be said that the SVC has unremarkable effect on performance of HWF during voltage sag condition. The voltage stability of the system is examined using voltage stability index as shown in Fig. 20.

Fig .20 the VSI shows that both cases HWF with or without SVC have the same voltage stability condition so that the performance of HWF without SVC is the same as HWF with SVC.

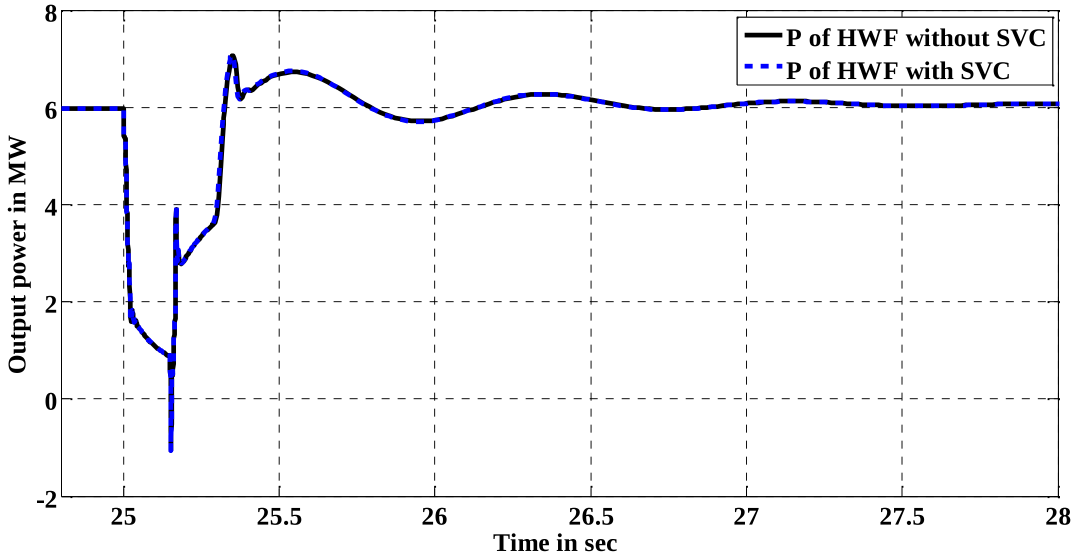

Figure (17): *Output power of HWF (with and without SVC) during three phase fault condition*

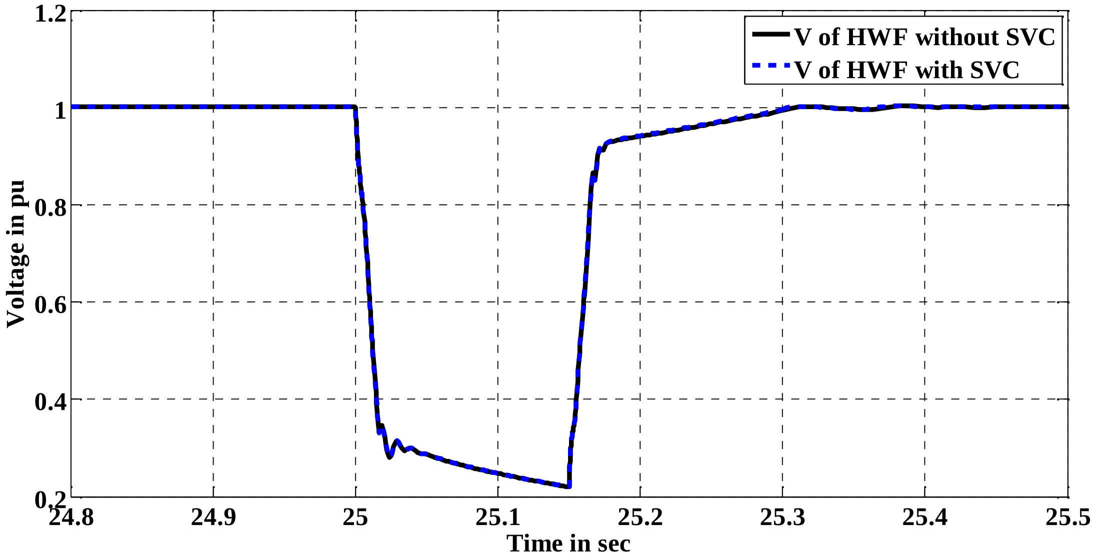

Figure (18): *Voltage of HWF (with and without SVC) during three phase fault condition*

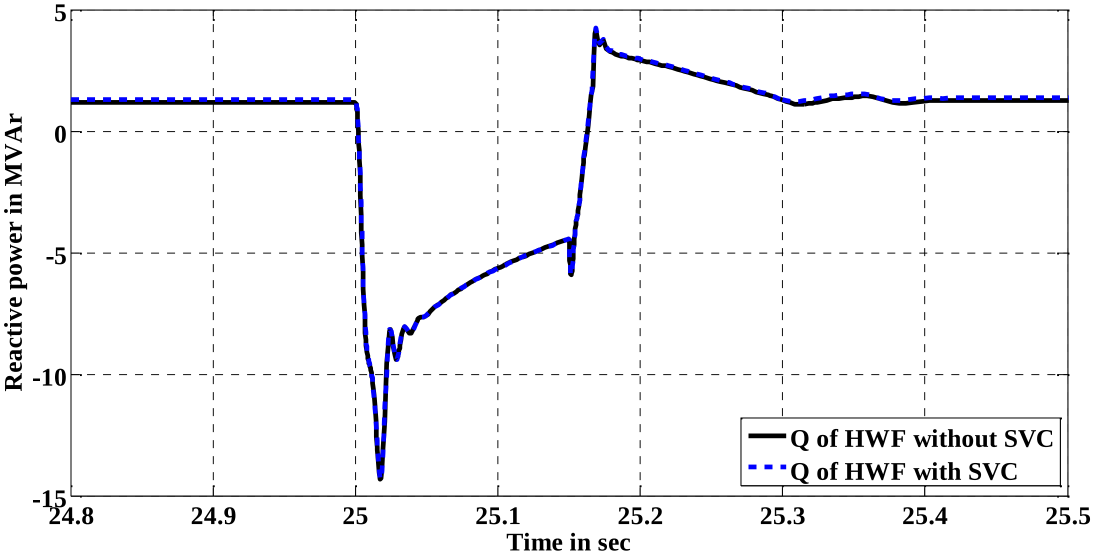

Figure (19): *Reactive power of HWF (with and without SVC) during three phase fault condition*

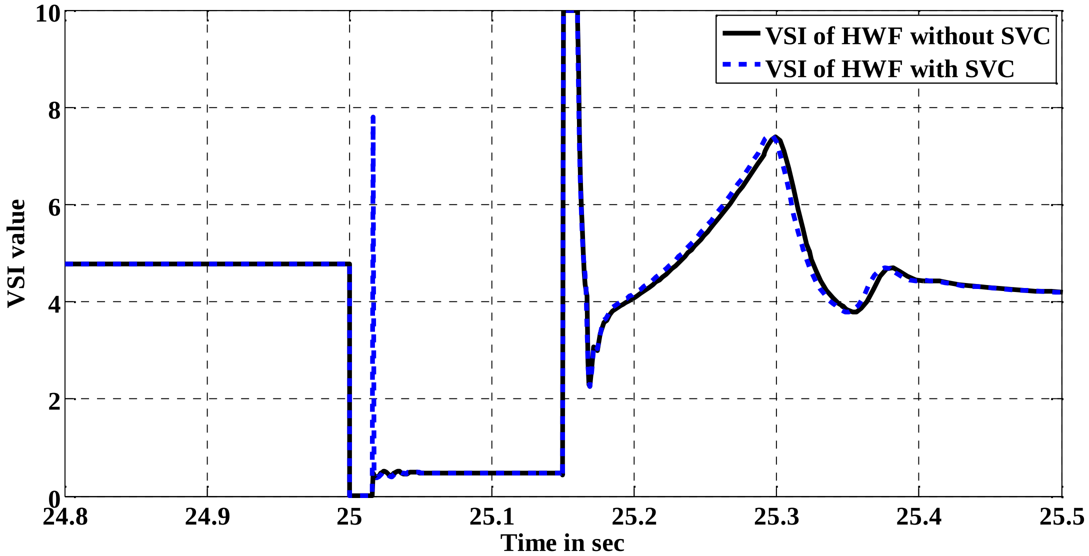

Figure (20): *VSI of HWF (with and without SVC) during three phase fault condition*

5. Conclusions:

In this paper, the performance of HWF Wind Farm (HWF) with and without static var compensator (SVC) with rating of 3 MVAR (equals to one third of wind farm rating) during single line to ground fault and three phase fault has examined. The impact of using SVC with HWF is useless. This means that the operation of HWF is not in need to use SVC to improve its stability. Consequently, the installation cost will be decreased in case of HWF compared to different types of wind farms which is based only one type of induction generators whatever SCIG or DFIG.

References:

[1] A. Movahednasab, S. M. Madani, M. M. Shahbazi, 'Modeling of a squirrel cage induction generator', IEEE Electrical Machines and Systems International Conf., pp 4267 – 4271, 17-20 Oct. 2008

[2] Rajiv Singh, Asheesh Kumar Singh, and Ashutosh Kumar Singh, "Transient Stability Improvement of a FSIG Based Grid Connected wind Farm with the help of a SVC and a STATCOM: A Comparison," International Journal of Computer and Electrical Engineering, Vol.4, No.1, February 2012.

[3] M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," Renewable Power Generation, IET, vol. 3, no. 3, pp. 308–332, Sept. 2009.

[4] J. Khazaie S. Badkubi D. Nazarpour M. Farsadi, “ANALYSIS AND IMPROVEMENT OF THE DOUBLY FED INDUCTION GENERATOR DURING GRID VOLTAGE FAULTS” International Journal on “Technical and Physical Problems of Engineering”, vol. 3, no. 4, pp. 80–85, December 2011.

[5] C. Y. Lee, S. H. Tsai, W. T. Liu, "The Impact of SCIG Wind Farm Connecting into a Distribution System", APPEEC 2009. Asia-Pacific Power and Energy Engineering Conf. 27-31 Mar. 2009.

[6] P. Sravanthi, K. R. Rani, J. Amarnath, S. Kamakshaiah, "Critical clearing time and transient stability analysis of SCIG based wind farm with STATCOM", IEEE Smart Electric Grid International Conf. 19-20 Sept. 2014.

[7] D. Gautam, V. Vittal, T. Harbour: "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems", IEEE Transactions on Power Systems, 2009; 24 (3): 1426 – 1434.

[8] L. M. Fernandez, F. Jurado, J. R. Saenz, "Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines", Renewable Energy 2008; 33 (1):129–140.

[9] Technical Connection Requirements, E.ON: Source: BDEW.

[10] MATLAB/Simulink Documentation, Available http://www.mathworks.com

[11] C. Zheng, M. Kezunovic, "Distribution System Voltage Stability Analysis with Wind Farms Integration", North American Power Symposium (NAPS), 26-28 Sept 2010

Nomenclatures:

p.u	Per-unit
AC	Alternative Current
DC	Direct Current
v_{ds}	Direct component of stator voltage
v_{qs}	Quadratic component of stator voltage
i_{ds}	Direct component of stator current
i_{qs}	Quadratic component of stator current
i'_{dr}	Direct component of rotor current with respect to stator
i'_{qr}	Quadratic component of rotor current with respect to stator
L_{ms}	Magnetizing inductance of stator
r_s	Stator resistance
L_s	Self-inductance of stator
P	d/dt
ω_r	Rotor Speed
r'_r	Rotor resistance with respect to stator

L'_r	Self-inductance of rotor with respect to stator
θr	Rotor angle
C_{rotor}	Rotor side converter
C_{grid}	Grid side converter
DFIG	Double Fed Induction Generator
SCIG	Squirrel Cage Induction Generator
HWF	Hybrid wind Farm
PCC	Point of Common Connection
q	Subscript refers to quadratic component of parameter
d	Subscript refers to direct component of parameter
Vdc	The voltage of dc bus of AC/DC/AC converter of DFIG wind turbines

Appendix A:

Appendix A: system parameters and Protection System Set Parameters

Parameters of SCIG wind turbine

Parameter	Value	Unit
Maximum power at based wind speed	1.5	MW
based wind speed	9	m/s
Operating wind speed	8	m/s

SCIG turbine Power Characteristic curve is shown in Fig 6

parameters of DFIG wind turbine

Parameter	Value	Unit
Maximum power at based wind speed	1.5	MW
based wind speed	9	m/s
Operating wind speed	8	m/s

DFIG turbine Power Characteristic curve is shown in Fig 7

Parameters of transmission line

Parameter	Value	Unit
Positive-sequence resistances	0.1153	Ω/km
Positive-sequence inductances	$1.05\ e^{-3}$	H/km
Positive-sequence capacitances	$11.33\ e^{-9}$	F/km
Length of transmission line	30	km

Parameters of AC/DC/AC converter

Parameter	Value	Unit

Rating of AC/DC/AC converter	0.83	MVAR
DC link normal voltage	1200	v
DC link total equivalent capacitance	20 e^{-3}	F

AC voltage and rotor speed protection

Parameter	Minimum Value (pu)	Maximum value (pu)	Delay time (sec)
AC under/over voltage for SCIG	0.85	1.1	0.15
Under/over rotor speed for SCIG	1	1.05	5
AC under/over voltage for DFIG	0.85	1.1	0.1
Under/over rotor speed for DFIG	0.3	1.5	5

AC current and DC voltage protection

Parameter	Maximum value	Delay time (sec)
AC current	1.1 pu	10
AC current unbalance	0.4	0.2
Voltage unbalance	0.05 pu	0.2
DC voltage	1900 v	0.001