IMPACT OF THE LOCATION OF FUZZY CONTROLLED STATIC VAR COMPENSATOR ON THE POWER SYSTEM TRANSIENT STABILITY IMPROVEMENT IN PRESENCE OF DISTRIBUTED WIND GENERATION

ABDELKRAM ZEBAR1, ABDELLATIF HAMOUDA1, KHALED ZEHAR2

Key words: Transient stability, Fuzzy logic control, Static var compensator (SVC), Distributed wind generation (DWG), Critical clearing time.

The energy renewal highlights wind energy system the prominent ways to turn down the environment pollution. The integration and penetration of these energy sources in power system have tended to be a dare for network managers, mainly, with wind turbines that do not tighten control of reactive power. In this paper, a fuzzy logic based supplementary controller for static var compensator (SVC) is evolved which is utilized for decreasing the rotor angle oscillations and to patch up the transient stability of the power system involving a distributed wind generation. Generator speed and the electrical power are selected as input signals for the fuzzy logic controller (FLC). Several fault disturbance simulation results are treated to emphasize the effective upshot of the suggested controller in a multi-machine (IEEE 30-bus) power system.

1. INTRODUCTION

Recently, the wind power generation included in the standard grid showed a further increase, in a significant way so, the electric utilities grid codes are forced to be revised, thus the reliability in systems with high wind energy diffusion will be guaranteed [1].

Transient stability, as it is commonly referred to, is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance [2]. The stability of the power systems which already existed is becoming to be a subject of significance, as wind energy is increasingly involved in to power systems.

A SVC is a member of flexible alternating current transmission system (FACTS) family primarily used to regulate bus voltage by injecting controllable reactive power into the system. It is also capable of improving transient stability
and damping of a power system by using some auxiliary signals superimposed over its voltage control signals [3, 4]. Various approaches are available for designing auxiliary controllers in SVC. Fuzzy logic control approach is an emerging tool for solving complex problems whose system behavior is complex in nature. An attractive feature of fuzzy logic control is its robustness in system parameters and operating conditions changes [5]. The critical clearance time (CCT) of a fault is generally considered as the best measurement of severity of a contingency and thus widely used for ranking contingencies in accordance with their severity [6, 2].

In this study the numerical integration method is needed for the sake of getting the accurate CCTs.

This suggested work aims at enthusing over the real outcome of the distributed wind generation (DWG) based on conventional fixed speed induction generator on the transmission systems. That is to say; to what extent and by what means the integration of large amounts of wind generation under fault condition influences the transient stability of the transmission system. Furthermore, the influence of SVC devices and their location with various penetration levels of DWG are in turn surveyed.

In natural, it has been conducted a particular comparative study between the SVC with and without fuzzy controller. total input signals such as rotor speed (ω) and rotor angle differences (Δδ) are handled as input to the fuzzy controller.

2. MATHEMATICAL MODEL

This section gives a mathematical model for the power system network which includes modelling of synchronous generator, DWGs, and SVCs.

2.1. SYNCHRONOUS GENERATOR

With some typical assumptions, the synchronous generator can be modelled by the following set of nonlinear differential equations [7]:

\[ \frac{d\delta}{dt} = \omega_0 \omega_s - \omega_s, \quad (1) \]

\[ \frac{d\omega}{dt} = \frac{(P_m - E'_q I_q - (x_q - x'_q) I_d q I_d q - D\omega)}{2H}, \quad (2) \]

\[ \frac{dE'_q}{dt} = \frac{(E_{f d} - E'_q + (x_d - x'_d) I_d q)}{T'_{d \delta}}, \quad (3) \]

where \( E_{f d} \) is the equivalent emf in the exciter coil, \( \delta \) is the power angle of the generator, \( \omega \) is the rotor speed with respect to a synchronous reference, \( E'_q \) is the
quadrature-axis transient voltage, $\omega_s$ is the absolute value of the synchronous speed in radians per second, $H$ is the inertia constant of the generator, $D$ is the damping constant of the generator, $T_{d0}'$ is the direct-axis open-circuit transient time constant of the generator, $x_d$ and $x_q$ are the d- and q-axis synchronous reactance, respectively, $x_d'$ is the d-axis transient reactance, $I_{dg}$ and $I_{qg}$ are the d- and q-axis components of the stator current, respectively.

2.2. DISTRIBUTED WIND GENERATION

A proper equivalent model can be easily obtained for fixed-speed wind turbines where a one-to-one correspondence between wind speed and active power output exists. In this case, aggregation is performed by adding the mechanical power of each wind turbine and by using an equivalent squirrel cage induction generator (SCIG) which receives the total mechanical power [8, 9].

A simplified transient model of a SCIG can be described by the following algebraic-differential equations [9]:

$$\frac{dE'_{dr}}{dt} = \frac{E'_{dr} + (x - x')I_{dr} + S\omega_s T_0' E'_{qs}}{T_0'}, \quad (4)$$

$$\frac{dE'_{qs}}{dt} = \frac{E'_{qs} + (x - x')I_{qs} + S\omega_s T_0' E'_{dr}}{T_0'}, \quad (5)$$

$$\frac{dS}{dt} = \frac{T_m - T_e}{2H_g}, \quad (6)$$

$$\left(V_{ds} + jV_{qs}\right) = \left(R_s + jx'\right)(I_{ds} + jI_{qs}) + j\left(E'_{dr} - E'_{qs}\right), \quad (7)$$

Here, $x' = x_s + x_m x_r/x_m + x_r$ is the transient reactance, $R_s$ is the stator resistance which is assumed to be zero, $x_s$ is the rotor reactance, $x_m$ is the magnetizing reactance, $x = (x_s + x_m)$ is the rotor open circuit reactance, $T_0'$ is transient open circuit time constant, $T_m$ is the mechanical torque, $S$ is the slip, $T_e = \left(E'_{dr} I_{ds} - E'_{qs} I_{qs}\right)$ is the electrical torque, $E'_{dr}$ and $E'_{qs}$ are the direct and quadrature axis transient voltages respectively, $I_{ds}$ and $I_{qs}$ are the direct and quadrature axis currents respectively, and $\omega_s$ is the synchronous speed. The DWG penetration level in the system is defined as [10, 11]:

$$\% \text{penetration-level} = \frac{P_{DG} \cdot 100}{(P_{DG} + P_{CG})}, \quad (8)$$

where $P_{DG}$ and $P_{CG}$ are the amount of total active power generated by DWG and centralized generation respectively.
2.3. STATIC VAR COMPENSATOR WITH FUZZY LOGIC CONTROL

A SVC with firing control system can be tackled in order to get a sort of simplicity by a first order model depicted by a gain $K_{SVC}$ and time constants $T_1$ and $T_2$ as illustrated in Fig. 1. The fuzzy controller provides an auxiliary control, which is viewed as an add to the voltage feedback loop.

![Fig. 1 – Static var compensator simplified control scheme.]

The additional control loop of the SVC utilises balancing signals like speed, frequency, phase angle difference etc. to touch up the dynamic performance of the system [5].

A Mamdani type double input single output (DISO) fuzzy linguistic controller has been designed which has the following four stages of (1) fuzzification, (2) rule- base, (3) inference Mechanism and (4) defuzzification [11]. The fuzzification process interprets the inputs as linguistic values. Inference uses a knowledge base of rules to determine the output sets for the input linguistic values. Finally, the defuzzification process uses the output of the inference to derive a single “crips” output values [12, 13].

In the presented FLC, the input signals are rotor speed ($\omega$) and rotor angle differences ($\Delta\delta$), and the resultant output signal is the voltage. Membership functions of the input and output signals are exposed in Fig. 2 in that for both of them Five linguistic variable are assigned, including, positive big (PB), positive small (PS), zero (ZE), negative small (NS) and negative big (NB). Based on the knowledge and experience, the rules are evolved 25 rules were developed with two inputs and five linguistic term. This is shown in Table 1.
Fig. 2 – Membership functions of $(\Delta \delta)$, $(\omega)$ and $(V_{FLC})$.

Table 1

<table>
<thead>
<tr>
<th>Voltage of FLC $(V_{FLC})$</th>
<th>Rotor angle differences $(\Delta \delta)$</th>
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<td>rotor speed $(\omega)$</td>
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<td>PS</td>
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<td>PB</td>
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In order to make up which rules apply to the current situation, in inference mechanism all the rules are compared to the inputs. After the matching process the needed rules are fired. The controlled output $b_{svc}$ is determined for the multiple input conditions. The defuzzification produces the final crisp output of FLC with the fuzzified input [5]. The centroid defuzzification technique is used to compute the output of the fuzzy logic controller which is the duty cycle [14]:

\[
D = \frac{\sum_{j=1}^{n} \mu(D_j) - D_j}{\sum_{j=1}^{n} \mu(D_j)},
\]

where $\mu(D_j)$ is the membership function of duty cycle $D$ for point $j$ and $D_j$ is the duty cycle $D$ for point $j$.

3. SIMULATION RESULTS

Simulation studies with programs developed under the environment of MATLAB software are conducted in this section to study the influences of the SVC devices on the 30-bus power system entailing a vast DWG. The system is depicted in Fig. 3 and its data have been referred to [15]. The loads are pictured in
constant impedance model. The simulation results clear up that the application of SVC in the test system influences the system transient stability variously in regard of the DWG location, the DWG penetration level, and the SVC location.

![Diagram of the IEEE 30-bus examination system](image)

Fig. 3 – The IEEE 30-bus examination system.

### 3.1. EFFECTS OF DWG ON POWER SYSTEM TRANSIENT STABILITY

To detect the outcome of DWG and the effect of its location on power system transient stability, a DWG is attached to each of the twenty-four load buses in the 30-bus test system. Three cases have been studied. The base case, in which we consider the original system without any DWG. In case 2, we consider a DWG at bus 10 with a penetration level of 20%. In case 3, we consider a DWG at bus 24 with a penetration level of 20%. The percentage of penetration level is calculated according to equation (8).

In the situation where the load increases in the buses 10 and 24, the SCIG based DWG at the respective busses will generate an active power, equating the amount consumed by the load. However, for the sake of generating this necessary active power, the SCIGs requirement to consume reactive power from the network. To compensate for this reactive power, a capacitor bank is linked to the terminal of each SCIG and consequently, the power factor is equal to unity.

As insofar the line between buses 1 and 2 of the test system, a three phase to ground fault is manipulated i.e. Generator 1 is the closest generator to the fault place and hence it possesses the prominent rotor speed deviation for this fault. The fault clearing time (FCT = 260 ms).
The results of the simulation on the rotor speed deviation of generator 1 of the mentioned fault are cleared up in Fig. 4. It is stated that the system with a DWG connected to the bus 10 maintains its stability. However, the system without and with a DWG connected to bus 24 loses its stability.

![Fig. 4 – Rotor speed deviation of generator 1 for the fault occurred on line 1–2.](image)

### 3.2. IMPACTS OF DWG FLOW PERCENTAGE ON THE TRANSIENT STABILITY

To treat the impact of the DWG flow percentage on the transient stability, the mentioned fault in the previous subsection is applied again. Two cases are considered: DWG at bus 10 and DWG at bus 24. The flow percentage of DWG rises by a factor of 5% from 0% up to 30%.

![Fig. 5 – Diagram of CCT versus penetration level of DWG.](image)
In Fig. 5 the CCT for different penetration levels (i.e. penetration levels of 0, 5, 10, 20, 25, and 30 %) in IEEE 30-bus system is shown and compared in the two cases. It could be viewed that a rising DWG flow percentage in the power systems will ameliorate the transient stability of the system and the locations of this DWG have an effect on power systems transient stability enhancement.

3.3. EFFECTS OF SVC ON POWER SYSTEM TRANSIENT STABILITY IN THE PRESENCE OF DWG

The use of the SVC to amend power system transient stability in the presence of DWG is evaluated in this subsection. At the outset, the SVC is not equipped with a FLC controller.

The 30-bus system is operated with the DWG at bus 10 and with/without the SVC. Three instances are manipulated. Without SVC case, with the SVC at bus 30, and with the SVC at the point of common coupling (PCC) where the DWG is connected. With regard to the line between buses 1 and 2, close to bus 1, a three phase to ground fault is applied. The fault is cleared after 280 ms.

In Fig. 6 it can be figured that the system after 280 ms with the SVC at PCC remains stable. However, the system without and with the SVC at bus 30 loses its stability.

In Fig. 6 the system responses after 280 ms with the SVC at PCC.
3.4. IMPACTS OF FUZZY LOGIC CONTROLLER FOR SVC ON POWER SYSTEM TRANSIENT STABILITY ENHANCEMENT IN THE PRESENCE OF DWG

For the sake of assessing the ability of the suggested FLC a comparative study has been tackled between the SVC with/without fuzzy controller. The output of FLC versus inputs is shown in Fig. 7. The 30-bus system is operated with the DWG at bus 10, the SVC at PCC and with/without the FLC. The mentioned fault in the previous subsection is applied again. The fault is cleared after 290 ms.

Simulation results on the rotor angle differences of six generators for the mentioned fault are cleared in Fig. 8. It could be figured as follows the system after 290 ms with the FLC stays up stable. However, the system without FLC loses its stability.
4. CONCLUSION

Modern electric power systems' operation, control and stability have been heavily affected by the rising penetration of energy sources renewal, increasing demands, restricted resources, and deregulated electricity markets power systems. FACTS devices like SVC are power electronics counted reactive compensators, linked to a power system and are able of evolving the power system transient performance and the quality of supply. This article investigates the implementation of a fuzzy logic counted auxiliary control for an SVC to attain the transient stability amelioration of power systems containing a large DWG. A SVC with FLC is situated at appropriate places in a 30-bus multimachine power system incorporating a massive DWG. The survey states that the high flow of DWG in the transmission system has an effective outcome upon the transient stability. At last, it could be stated that the proposed FLC for SVC placed at suitable locations could be handled as a forceful tool to improve the transient stability with respect to transmission system incorporating large amounts of DWG.

Received October 30, 2013

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