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Enhancement of Reliability of Process Power Plant by Connecting SVC in Generator Bus during Grid Fault

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Abstract

Fault clearing time plays an important role in maintaining power system stability and process survivability during major system faults under a variety of system configuration and topologies. Grid disturbance in the power system presents a very distinct challenge; lack of a utility interconnection hinders the system's ability to recover from loss of generation. The key factor in plant survivability during a grid fault is optimal use of a fast acting governor and a Flexible Alternating Current Transmission System device (FACTS) to maintain power system stability. In this paper, the core objective is to increase the critical fault clearing time of captive generator sets during a grid fault without violating the transient stability criteria recommended in IEC standards. As a remedial measure, a static VAR Compensator (SVC) was connected to the generator bus. For simulation purposes an IEEE General Steam-Turbine (STM) governor model and an IEEE AC5A excitation model were considered. During a grid fault the transient performance of captive generator sets was observed with and without connecting SVC in generator bus.

Keywords: Captive generation; Critical Fault Clearing Time; Static VAR Compensator

1. Introduction

In the era of a deregulated power industry, any enterprise can sell power to the grid – it does not have to be a generation company. As a result, many process companies have shown a keen interest in setting up captive power plants in such a way that the captive unit is able to cater for their own load and excess power can be sold to the grid [1]. After a smart grid policy is introduced, plant owners have open access to sell the surplus power on the common trading platform. Consequently, this makes the prospect of building a captive power plant an attractive option for many process industries [2, 3].

The industrial sector is the largest energy consumer in the world and most industries now depend on their own generation rather than utility supply due to insufficient grid supply, poor power quality and higher tariff rates. Insecure power supply and higher tariff rates translate into higher production costs [4, 5, 6]. To cater for both essential and nonessential loads of the plant, captive generators generally run in parallel with the grid supply. Whenever the grid is disturbed due to a fault, power transmission parameters of grid start vary widely [7, 8], which may be detrimental to captive generators or process equipment. When a grid fault occurs it is recommended to isolate captive power plants from the grid as soon as possible to maintain the safety of captive generator sets [9]. This is commonly known as islanding. Essential loads of the plant shall be met by captive plants – to the extent possible – until the grid supply situation is normalized. K. Rajamani, U.K. Hambarde address the problem of islanding and a load shedding scheme for a captive power plant in [10]. Satvir Singh and J. S. Saini [11] address the problem of Fuzzy FPGA Based Captive Power Management during islanding. However, Satvir Singh and J. S. Saini did not address the issue of stability of the captive generator sets in their paper. It is very important to assess the transient stability performance of a captive generator before islanding from the grid [12]. Current industry practice is to disconnect all distributed generators within the critical fault clearing time after a grid fault occurs if the system has not regained stability [13, 14]. Voltage variation, frequency fluctuation and rotor angle variation are the transient stability index to access stability during the plant contingency period [15, 16, 17]. Transient stability limits depend on dynamic behavior of the network [18, 19, 20] such as machine damping, armature resistance of machinery, etc. Stability limits of a captive power plant (CPP) can be analyzed using equal area criteria or the Lyapunove method [21, 22]. Flexible Alternating Current Transmission System devices (FACTS) are generally used in

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power systems to improve dynamic control of the system and to damp out low frequency oscillation [23, 24, 25, 26, 27, 28].

When a captive power plant generates power over and above its internal load requirement and excess power is transmitted to the utility grid, any disturbance on the utility side forces the CPP to go into islanding mode if the disturbance is not removed within the critical fault clearing time. During this islanding condition a small captive generator set experiences total load throw-off on the utility side causing disturbance in the transient form. Most of the time this transient disturbance is not recovered immediately in terms of turbine speed, voltage variation etc. due to insufficient critical clearing time. This results in cascaded outages of generation units and processes suffer [17]. To avoid this situation a static VAR Compensator (SVC) connects with the generator bus to increase the time duration of sustaining grid fault without violating the transient stability criteria recommended in IEC standards. The models considered for simulation purposes were: the IEEE AC5A [29, 30, 31] excitation model – to control the excitation system of generators – and the IEEE General Steam-Turbine (STM) governor model, to control the speed of the generator [32, 33, 34, 35].

2. Profile of the power system

The system considered in this paper is a captive generation facility serving a process plant. The process plant has two independent power supply lines. In line 1 power is supplied through an 11 kV/415 V distribution transformer to the following: 415 V power and motor control center denoted as 4G11BuA, 4G11BuB, 4G13BUA, 4G13BUB, 4G12 and 4G13BUErm. The 11 kV/415 V plant distribution transformer is supplied by an 11 kV switchgear denoted as 11G1. The 11 kV switchgear takes supply from 12 MW Generator 1. Line 2 supplies power using an 11 kV/415 V distribution transformer for supplying power to the following power and motor control center referred to as 4G21BuA, 4G21BuB, 4G22BUA, 4G22BUB, 4G22Bu and 4G23BUErm. Line 2 takes supply from an 11 kV switchgear denoted 11G2. The 11 kV switchgear is connected with 13 MW generator G2. One (1) no. 415 V DG set (DG1) and one (1) no. HT diesel generator are installed as stand-by for the emergency condition during total blackout of the process plant [34].

Start-up power for the generators is generally available from the electric grid. Alternatively, an 11 kV diesel generator (DG2) is available to provide start-up power. A second turbine generator (G2) can also manage start-up power from the first turbine generator (G1), if already started (and vice-versa). The basic power system arrangement for all generators along with interconnection is shown in the key single line diagram, showing all circuit breakers prepared for the study. As per the system philosophy for feeding the process lines, G1 and G2 generally run parallel. However, in case one generator (G1 or G2) goes out of service the other generator can take over the total process plant load. The 11 kV, 12 MW & 13 MW generating units will be connected to 11 kV switchboards. Auxiliaries of this unit will be

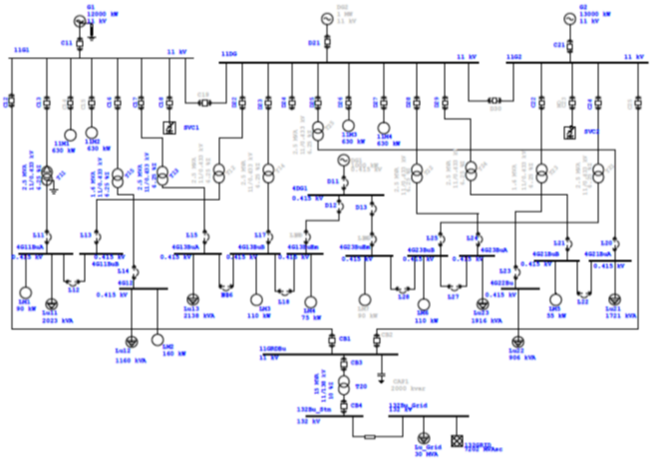

Figure 1: Network diagram for system study

fed from a 2.5 MVA distribution transformer connected to the said 11 kV switchboard. 15 MVA generator-transformers will be connected to a 132 kV switchyard. The 132 kV switchyard will be connected by a single circuit overhead transmission line for evacuating power to the grid. Upon occurrence of an emergency situation such as failure of generators, the plant has a facility to use a diesel generator (DG2) to supply the emergency load during main supply failure in order to keep the plant in operation. The above power supply arrangement is depicted in Fig. 1. The 132 kV buses and the plant 11 kV buses, generators, LT transformers and LT buses with lump loads and tie interconnects required for the study are shown in the network diagram. Static VAR compensators (SVC1 & SVC2) connect with both 11 kV generator buses. The purpose of Fig. 1 is to identify various equipment and buses with respective IDs used in the study.

2.1. Input data consider, for system study

The system information, shown on the single-line diagram, defines the system configuration and size of loads, generation, and equipment. Here, data values are considered as accurate as possible for simulation purpose. Rounding off does not include enough decimal places in certain parameters, otherwise the simulation could lead to incorrect outputs. The data used in the ETAP software modeling are indicated in Table 1.

3. Profile of excitation and turbine governor models

The excitation and turbine governor models below are considered. The basic model is taken from the IEEE recommended practice of excitation and turbine governor models for power system stability. Relevant studies appear in [29, 30, 31, 32, 33, 34, 35, 36, 37].

3.1. IEEE Type-AC5A excitation model

The basic diagram of the IEEE Type-AC5A excitation model is shown in Fig. 2.

Table 1: Data considered for models used in ETAP software

Model used	Specifications
Synchronous generator	Impedance model
	X_d" = 12, X"/R_a = 48, R_a% = 0.25, R_a = 0.014235 Ω, X_2 = 12, X_2/R_2 = 48, R_2% = 0.25, R_2 = 0.014235 Ω, X_0 = 12, X_0/R_2 = 48, R_0% = 0.25, R_0 = 0.014235 Ω
	Subtransient model
	X_d% = 110, X_q% = 108, $T_{d0'}$ = 56, S_{break} = 0.8, X_{d4}% = 116.93, X_{q4}% = 114.79, $T_{d0''}$ = 0.002, S_{100} = 1.07, X_d'% = 23, X_q'% = 15, $T_{q0'}$ = 3.7, S_{120} = 1.18, X_L% = 11, X_q'% = 12, $T_{q0''}$ = 0.02, Damping = 5, H = 1.7
	Machine model
	Generator type = Turbo Rotor type = Round rotor IEC Exciter type = 130% Turbine
	Exciter model
	Exciter type: AC5A Turbine Governor Model: IEEE General Steam Turbine (STM)
Inertia Constant	Generator inertia constant = 1.038 sec. Turbine inertia constant = 1.5 sec. (Assumed) Combined inertia constant = 2.538 sec.
Grid model	Nominal voltage = 132 kV Fault level of 132 kV switchyard Bus = 7201 MVA X/R ratio (3 ph) = 60, X/R ratio (1 ph) = 60
Generator transformer	Capacity = 15 MVA Primary voltage = 11 kV Secondary voltage = 138 kV Vector group = Ynd 11 Neutral grounding = Solid Impedance (+Seq) = 10% Impedance (-Seq) = 10%, X/R = 18.6
SVC	SVC Control Model – Type 1

The data considered in the IEEE Type-AC5A excitation model are shown in Table 2.

3.2. Turbine governor model type: IEEE General Steam-Turbine (STM)

The basic diagram of the turbine governor model is shown in Fig. 3.
The data considered in the IEEE STM type turbine governor model are shown in Table 3.

3.3. SVC model type-1

The basic diagram of the SVC model is shown in Fig. 4.
The data considered in the SVC model are shown in Table 4.

4. Results and analysis of study

4.1. Results of transient analysis

The transient stability study of the proposed network is performed in the following conditions.

- For a fault on the 132 kV grid side, the utility breaker tripped immediately and the fault is cleared within a few milliseconds.

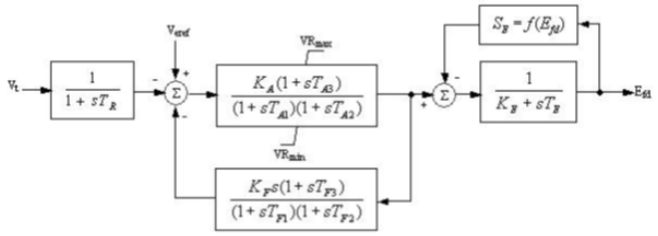

Figure 2: IEEE Type-AC5A excitation model

Table 2: IEEE Type-AC5A excitation model data

Parameter	Definition	Unit
VR_{max}	Maximum value of the regulator output voltage	7.3
VR_{min}	Minimum value of the regulator output voltage	–7.3
SE_{max}	The value of excitation function at Efd_{max}	–0.86
SE.75	The value of excitation function at 0.75 Efd_{max}	0.5
Efd_{max}	Maximum exciter output voltage	5.6
KA	Regulator gain	400
KE	Exciter constant for self-excited field	1
KF	Regulator stabilizing circuit gain	–0.03
TA1	Voltage regulator time constant	0.02
TA2	Voltage regulator time constant	0
TA3	Voltage regulator time constant	0
TE	Exciter time constant	0.8
TF1	Exciter control system time constant	1
TF2	Exciter control system time constant	0
TF3	Exciter control system time constant	0
TR	Regulator input filter time constant	0.005

Criteria for transient stability analysis.

1. When two generators are run in parallel and one source is running with the relative power angle of θ, then after removal of the fault this source should return to this power angle with minimum swing.
2. Voltage and frequency of the sources shall be within acceptable limits of +/-5% of rated voltage and +/-2.5% of rated frequency respectively.

The operations performed for the transient stability study are shown in Table 5.
The simulation results of the transient stability study for case-

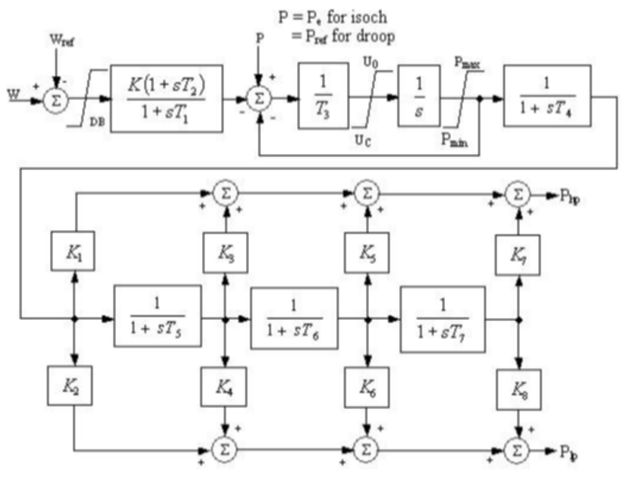

Figure 3: IEEE STM type turbine governor model

Table 3: STM type turbine governor model data

Variable	Description	Value
Mode	Droop	
Droop	Steady-state speed drop in second, %	5
DB	Speed deadband	0
K1	Partial very high pressure turbine power fraction	0.11
K2	Partial very high pressure turbine power fraction	0.11
K3	Partial high pressure turbine power fraction	0.11
K4	Partial high pressure turbine power fraction	0.11
K5	Partial intermediate pressure turbine power fraction	0.11
K6	Partial intermediate pressure turbine power fraction	0.15
K7	Partial low pressure turbine power fraction	0.13
K8	Partial low pressure turbine power fraction	0.13
Pmax	Maximum shaft power, MW, G1	12
	G2	13
Pmin	Minimum shaft power, MW	0
T1	Amplifier/Compensator time constant, s	0.1
T2	Amplifier/Compensator time constant, s	0
T3	Amplifier/Compensator time constant, s	0
T4	Amplifier/Compensator time constant, s	0.19
T5	Amplifier/Compensator time constant, s	11
T6	Amplifier/Compensator time constant, s	0.3
T7	Amplifier/Compensator time constant, s	0

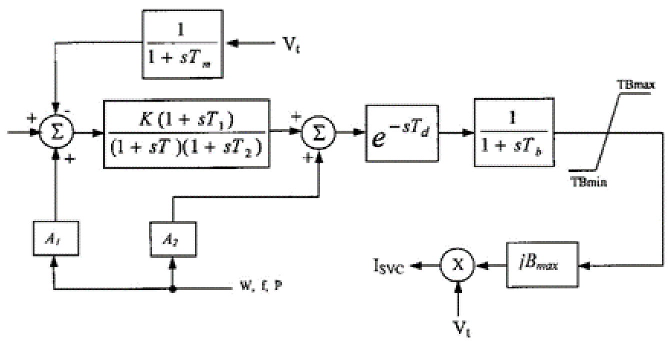

Figure 4: SVC type-1 model

Table 4: SVC model data

Variable	Description	Value
K	Voltage regulator gain	33.29
A1	Additional control signal gain	1
A2	Additional control signal gain	1
T	Voltage regulator time constant	0.06
Tm	Measurement time constant	0.001
Tb	Thyristor phase control time constant	0.004
Td	Thyristor phase control delay	0.001
T1	Voltage regulator time constant	0.5
T2	Voltage regulator time constant	1
TBmax	Maximum susceptance limit	1
TBmin	Minimum susceptance limit	−0.87

Table 5: Event of operation performed for transient stability study

Event	Time	Action	Excitation model used	Turbine governor model used	Status of SVC
			Case-1		
T1	0.5 sec	3Ph Fault on Grid bus	IEEE Type AC5A	IEEE General SteamTurbine (STM)	Without SVC
T2	0.585 sec	3 Ph Fault Clear			
			Case-2		
T1	0.5 sec	3 Ph Clear Fault on Grid bus	IEEE Type AC5A	IEEE General Steam-Turbine (STM)	With SVC
T2	0.610 sec	3 Ph Fault Clear			

1 and case-2 are depicted in Figures 5 and 6 respectively.

5. Discussion

The summary output of the transient stability performance of different cases (Case-1 and 2) is depicted in Table 6. The performance of the fault clearing time relative to power angle variation and frequency variation is covered in detail in Table 6.

6. Conclusions

As per the analysis it was observed that, during grid disturbance and after removal of fault, the first acting turbine governor system along with exciter and SVC plays an important role in maintaining the transient stability of the system. During selection of the turbine governor and excitation system the critical fault clearing time needs to be critically analyzed. From the transient stability study it is very clear that the turbine governor model with SVC performs better in terms of: frequency variation, voltage variation, damping oscillation and critical fault clearing time during a grid fault condition. With the use of SVC the critical fault clearing time increased from 85 ms to 110 ms during 132 kV grid bus fault. With the use of SVC the reduction in generator bus frequency oscillation results in reduced thermal stress in the turbine system whereas the increment in the fault clearing time means improved plant reliability. Increments in critical fault clearing time also help the plant operator to safely perform the islanding operation with respect to the captive generator. Thus the use of SVC along with exciter and turbine governor model increases the service life of costly equipment like boilers and turbines and it enhances the reliability of captive power plants.

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Table 6: Summary of transient stability analysis

Case 1	
Fault clearing time	85 ms
Relative power angle	36.8° (Fig. 5(a))
% of max. frequency variation	+/-2.5% (Fig. 5(b))
% of voltage variation	4.5% (Fig. 5(c))
Remarks	When two generators G1 and G2 are run in parallel with grid and sources are running with relative power angle of 36.8°, then after removal of the fault, this source returns to initial power angle with minimum swing. Frequency variation of generator bus is within the acceptable limits of +/-2.5%. Voltage variation of generator bus is within the acceptable limits of +/-5% of rated voltage. The Figures (5(a), 5(b), 5(c)) satisfies the criteria of transient stability performance. Hence, the critical clearing time of grid fault is 0.085 sec.
Case 2	
Fault clearing time	110 ms
Relative power angle	36.8° (Fig. 6(a))
% of max. frequency variation	+/-0.4% (Fig. 6(b))
% of voltage variation	1% (Fig. 6(c))
Remarks	When two generators G1 and G2 are run in parallel with grid and generators are running with relative power angle of 36.8°, then after removal of the fault, these generators return to initial power angle with minimum swing. Frequency variation of generator bus is within the acceptable limits of +/-2.5%. After removal of a fault generator bus frequency damps out much faster compared to the other two cases considered for analysis. Voltage variation of generator bus is within the acceptable limits of +/-5% of rated voltage. Figures (6(a), 6(b), 6(c)) satisfies the criteria of transient stability performance. Hence, the critical clearing time of grid fault is 0.110 sec. From the simulation results it is very clear that the performance of the turbine governor model along with SVC significantly improves the transient stability index and critical fault clearing time of captive generator sets.

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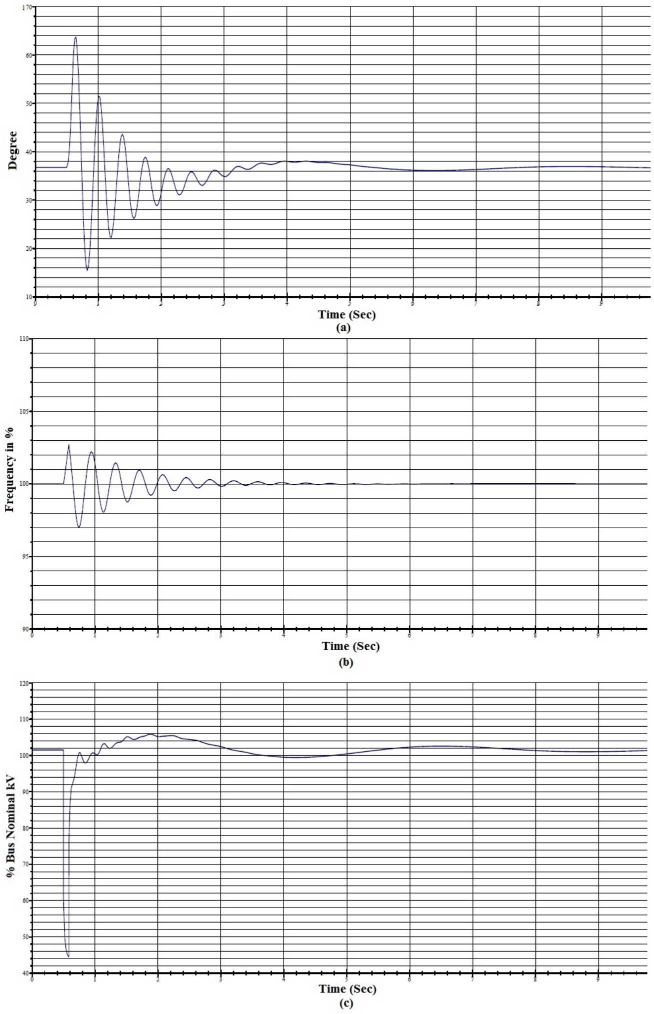

Figure 5: (a) Relative power Angle in Deg Vs Time in Sec. for generators G1 & G2, (b) % of Gen. Bus Frequency Vs Time in Sec for generators G1 & G2, (c) % of Gen Bus Voltage Vs Time in Sec for generators G1 & G2

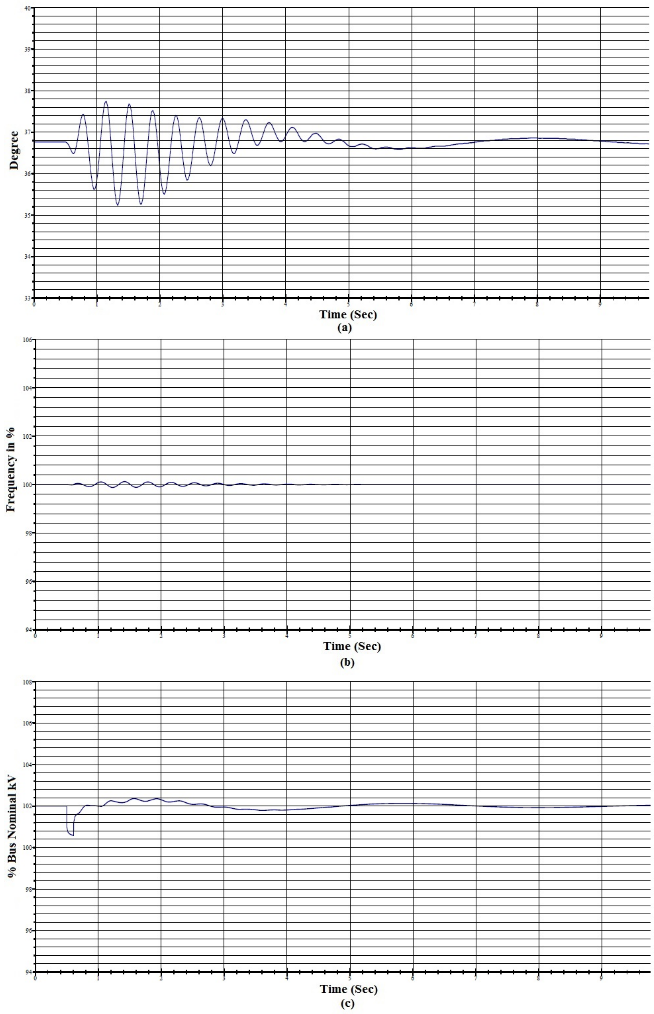

Figure 6: (a) Relative power Angle in Deg Vs Time in Sec. for generators G1 & G2, (b) % of Gen. Bus Frequency Vs Time in Sec for generators G1 & G2, (c) % of Gen Bus Voltage Vs Time in Sec for generators G1 & G2

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