Smooth Evacuation of Power in Grid Connected Small Hydro Power Stations by Application of SVCs

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Received: 28.02.2015 Accepted:26.05.2015

Abstract- Unlike the generators in large hydro power stations, which operate in voltage control mode, the generators in small hydro power stations (SHPs) are forced to operate in power factor control mode due to their limited reactive power support. In fixed power factor operation, smaller variations of voltage at the evacuation bus are managed by on load tap changing at the generator transformers. However, during large and frequent variations in voltage, such SHPs face difficulty in evacuating the power due to delayed response by the operators and inadequate tap settings of the generator transformers. This paper explores the use of static VAR compensators (SVCs) to overcome these practical limitations encountered by SHPs so as to ensure smooth evacuation of every unit of real power generated by such units to the neighboring grid in a grid connected power system scenario. The proposed simulation has been tested under some worst system conditions and case studies conducted on the IEEE 30-bus test system by way of connecting the SHP units to the most critical system bus of the test system with SVC control at the local bus. The test results have been validated with the support of power flow tools on a Matlab based Matpower platform. It is observed that the results obtained through application of SVCs are far more promising than those of the results obtained from OLTC transformer control mechanism only.

Keywords: SHP generating unit; Evacuation of real power; OLTC; L-index; SVC.

1. Introduction

In a physical power grid, the situation in the utility front is far worse than predicted. In order to understand the real problem, it has always become important to make proper selection of parameters which in fact play a crucial role for every utility. As the demand grows indefinitely, the available resources of the utility remain overstressed all the while. To overcome various disadvantages of large-scale hydro plants, it is proposed in the literature [1-3] to install SHPs in the regions that have potential for generating hydro electricity. Clean energy at a competitive cost, less affected by rehabilitation and resettlement (R&R) problems vis-a-vis large hydro power plants, meeting power requirements of remote and isolated areas and availability of mature and largely indigenous technology, small hydro power plants (SHP) are growing at a faster rate all over the world. However grid connected SHPs faces challenges in maintaining continuous evacuation of power during the peak seasons where plenty of water is available in the river stream. The utilities and the local governments have devised various policies so as to encourage private and public entrepreneurs for setting up of their own small hydro power generating units in order to supplement their generation to the grids. As a result of this, many firms have gone a long way in setting such units with the help of schemes and technical support available with them.

However, in the long run, many of such SHP units have realized that the actual purpose is not met that easily. Such SHP units eventually face a lot of difficulties while evacuating the real power generated to the physical power grid. This is because of the fact that the SHP stakeholders often lack a thorough system study prior to commissioning such units, which seem to be mandatory in view of the connectivity to large power grids for ensuring smooth evacuation of power at all possible system conditions. One of the main problems faced by such SHPs deals with power evacuation under varied voltage conditions at the pulling substation i.e. the bus where the SHPs are connected to the grid. In order to focus such issues in a genuinely practical way, a thorough study is being conducted on a practical situation that encompasses a small hydro power generating unit being connected at the weakest system bus of the standard IEEE-30 bus test system. In view of the above aspects, the results obtained have been validated with the robust continuation power flow analysis on a Matlab and Matpower platform that establishes smooth power evacuation while overcoming the limitations faced by SHP units.

2. Evolution of Small Hydro Power (SHP) Units

Small hydro plants are basically “run-of-river” type. They generate electricity ranging from few kilowatts to few megawatts. A detail classification of SHP units categorized as Micro, Mini and Small Hydro projects is presented below:

i) Mini hydro-10 KW to 99 KW;

ii) Micro hydro-100 KW to 999 KW;

iii) Small hydro- 1 MW to 25 MW.

The low utilization rate of the world’s SHP potential could be attributed by several factors such as (i) challenges faced in setting up plants in remote terrain; (ii) delays in acquiring land and obtaining statutory clearances; (iii) inadequate grid connectivity; (iv) high wheeling and open access charges in some States; and (v) preliminary survey and review for the technical aspects.

The execution and evacuation challenges faced by SHP projects [4] are much higher than any other renewable energy sources, for a variety of reasons. Because of reactive power constraints, most of SHP plants face evacuation problem under fluctuating voltage conditions. In order to get the minimum generating cost, SHP units mostly prefer to operate at fixed power factor mode. Yet, running the plant in fixed power factor mode is also not free from difficulties, as discussed later in this paper. The generators available at all small hydro system are of synchronous type. In large hydro units generators usually operate in voltage control mode in which the generator adjusts its reactive power requirements (both generation and absorption) as needed by the system to maintain required voltage at the generator bus. However in small hydro units, generators may possibly operate in two modes [5], such as Power factor control mode (under steady state conditions.) and Voltage control mode (under varying voltage condition including transients). The small run-off-river hydro power plants can control the network voltage by limited control of reactive and active power by the concept of virtual power plant [6-7]. Within a virtual power plant, a group of distribuited generators can be controlled by an energy management system, which is able to communicate with the distribuited generators. But this method need not only more than one distribuited generating system but needs sophisticated hardware and software in communication technology.

Hence, most SHP generators use reactive power control by help of transformers with on load tap changer. In power factor control mode, the generators supply a fixed amount of reactive power for a particular value of active power output at the cost of varying generator bus voltage. In order to keep the generator bus voltage at the stipulated level or within safe limits, the tap of generator-transformer (GTs) is changed, following any change in voltage at the puling substation bus. In other words, the reactive power management is done with the help of on load tap changing of the Generator transformers. In voltage control mode of operation, the controller adjusts the excitation of the generator to achieve the target voltage at the generator bus.

3. Identification of Weak Buses

Grid connected SHPs are normally situated in remote terrain to which the available grid connectivity is at medium voltages (11KV or 33 KV). The point of common coupling (PCC) for such SHPs are normally at weak buses as they are far from large grid substations. Hence the fluctuation at these buses is large and frequent. To realise this situation for the case study, IEEE-30 bus test system is considered and the SHP is connected to the system at it is weakest bus.

The criterion for identifying the weakest bus in the system has been addressed by many [8-11] in the existing literature. The following procedure has been implemented in this work.

The Line index (L-index) method [12-14] is another method which uses system impedance matrix as the study parameter. Kessel et al. [13] developed the L- index based on the solution of the power flow equations. However, the L-index is a quantitative measure for the estimation of the distance of the actual state of the system with respect to the limiting state of voltage stability. The L-index performs as a good indicator, describing the stability of the complete system.

For a given system, let ‘n’ represent total number of buses, ‘g’ represent number of generator buses and ‘(n-g)’ represent remaining load buses. Using the load flow results the L-index for the jth load bus (L_j) is computed as shown in Equation (1).

$$L_j = \left| 1 - \sum_{i=1}^{g} F_{ji} (V_i / V_j) \right| \tag{1}$$

All the terms within the sigma on the RHS of Eq. (1) are complex quantities. The value F_{ji} are obtained from the Y bus matrix as given in Equation (2).

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} Y_{GL} \\ Y_{LG} Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{2}$$

Where IG, IL, VG, VL represent the currents and voltages at the generator nodes and load nodes. Rearranging Equation (2) we get the desired parameter ‘F_{ji}’ as indicated in Equation (3).

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} F_{LG} \\ K_{GL} Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{3}$$

The L-indices for a given load condition are computed for all load buses. An L-index value away from 1 and close to 0 indicates an improved voltage stability margin. Thus, higher values for L-indices are indicative of most critical buses and their proximity to voltage collapse.

The Voltage Collapse Proximity Indicator (VCPI) introduced by Kessel et.al. [13] utilizes the information obtained from a normal load flow solution. The method can be used to determine local indicators corresponding to each load bus. Voltage Collapse Proximity index is used in Power System for voltage collapse detection of buses. The method uses the bus voltage magnitudes, voltage phase angle and the network admittance matrix for the prediction. In this method, the index is computed taking Centroid of the voltages i.e., averages of the voltages of the generator buses. The centroid value for i^th load bus is given by Equations (4) and (5).

$$C_i = \frac{|V_{cg} - V_i|}{|V_i|} \tag{4}$$

$$V_{cg} = \frac{\sum_{i=1}^{g} V_i}{g} \tag{5}$$

4. Devices and Their Application for Improvement of Voltage Stability

FACTs devices are being increasingly utilized in many electric power systems to enhance voltage control and system dynamic performance [15]. Among the existing devices, SVCs have been found more suitable for improvement of voltage regulation and enhancement of voltage stability margins as well [16, 17]. In most cases of SVC application, reactive power is locally controlled to maintain the required voltage at the connected bus.

SVCs are shunt connected static devices, which can generate and/or absorb the reactive power as per the specific requirements of the power system. A typical SVC is shown in Figure 1 consists of Thyristor-Switched Reactors (TSRs) and Thyristor-Switched Capacitors (TSCs) or fixed Capacitor in parallel. The output is controlled in steps by sequentially switching of TCRs and TSCs. The need for harmonic filtering as part of the compensator scheme could be eliminated by stepwise switching of reactors rather than continuous control. Figure 2 shows various models of SVCs used in power flow simulation. The first model considers SVC as variable impedance, which is adapted automatically to achieve the voltage control. This is called the passive model and its main disadvantage is the changing of nodal admittance matrix whenever there is a variation in the operation conditions of the power grid.

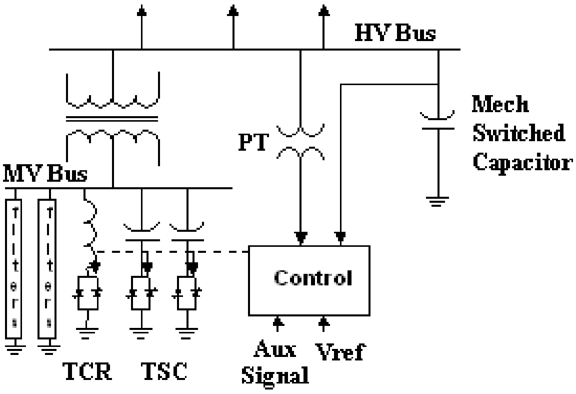

Fig. 1. Internal structure of an SVC

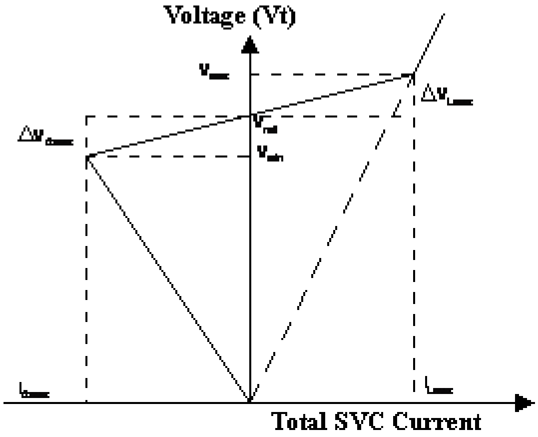

Fig. 2. V-I Characteristics of an SVC

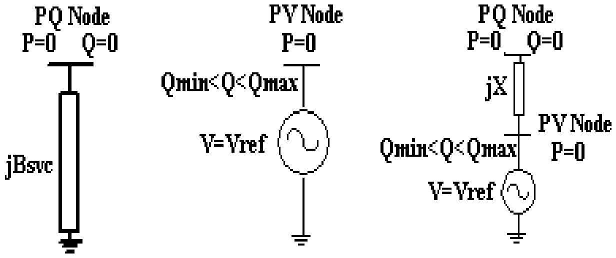

Fig. 3. SVC Passive, Active and Practical model

The second model, called active model, represents SVC as a nodal power injection, where a reactance equivalent to slope of the V-I characteristic, shown in Figure 3 is added between the auxiliary node and the node of coupling to the system (usually referred as a PQ node).

5. Problem Formulation

Loads at all P-Q buses play an important role for determining the stable operation of the system as far as voltage instability is concerned. Since voltage instability is also treated as load instability, the idea of obtaining information about the most critical bus in a system through simultaneous loading of existing loads at all buses is projected in this work. In order to accomplish this, the existing base case load, at all load buses are increased in gradual steps simultaneously and the percentage change in voltage as a function of change in real power demand is compared among the load buses over a particular range of variation. The load bus indicating the largest percentage change of voltage is considered as the most critical bus of the system.

In order to visualize the problem in grid connected SHPs, the standard IEEE-30 bus system is considered in this paper. Subsequently, the SHP unit is connected at the weakest bus of this system to study the possibility of power evacuation to the grid. The evacuation is done with varied voltages at the receiving bus. The voltage variation is achieved by simultaneous load variation at all the buses of the test system. The idea of connecting the SHP at the weakest system bus is to simulate the worst scenario of voltage variation before the SHP and hence to study whether smooth evacuation of power is feasible. However, it may be more accurate to mention at this stage that the SHP units also fail to follow smooth power evacuation to the grid under some critical system conditions. Thus, the authors were motivated for implementing the novel application of SVCs so as to circumvent the existing difficulties faced by the SHP units under those critical conditions. Though it is observed that, in few cases evacuation of power is possible with the available tap settings of the OLTC, yet the scheme offer the following limitations.

i. Since the taps are changed manually, it becomes mandatory on the part of the operator attending the OLTC to remain extremely watchful in response to any voltage changes at the pulling bus.

ii. Since the SHP has limited generation capability, as compared to standard generators of the existing grid, it does not become viable to assign PV bus status to the SHP bus. Therefore the load flow is carried out considering PQ status for the SHP bus (same as the status of the pulling bus), which invokes changes in the voltage at this bus following any changes in the grid. By using OLTC transformers the voltage control takes place in discrete steps, thus imposing an increment in the SHP bus voltage following a sudden change in the OLTC tap. Hence the SHP bus voltage is observed to remain on the higher side than the nominal voltage most of the times.

iii. Many existing grid connected SHPs are in operation without a system study. This may lead to inability in evacuating the rated power to the grid with existing transformer tapings. Also, in case of capacity hike of an SHP, the existing transformers may not be suitable to evacuate the additional power with the existing feeder.

iv. In case of an SHP connected with a strong grid where the voltage profile is very stiff, the evacuation problem become more severe.

v. In case multiple identical generators operate in parallel with constant power factor mode in an SHP, it becomes essential to share the common load equally among them in order to maintain uniform voltage profile. However following any discrepancy in equal sharing of real power, the respective reactive power generation becomes unequal, which leads to unequal voltage at their local buses causing circulating current flow in the local loops. Thus, it is causing frequent tripping of the affected units as sensed by the reverse power flow relay.

The above limitations give a scope for use of FACT devices in this proposed work to mitigate such problems.

In actual geographic conditions, the SHP units are situated at remote locations that may be far off from the grid structure. In order to connect them to the grid, often a secondary feeder may be essential. This feeder acts as the link or interconnection between the SHP and a specific bus point of the grid usually denoted as the evacuation point. As long as the evacuation point remains strong and stable, the evacuation is made safely. However, the real problem mounts if the evacuation point happens to be a weak bus in the system. It is of paramount importance to meet this challenge and ensure smooth evacuation at all times, which in fact propelled the authors for conducting a study to identify the weakest system bus. The objective of finding the weakest bus in the given (IEEE-30 bus) system and assigning this bus the status of evacuation point is viewed genuinely in this work.

6. Case Study

In this paper, the study is based on evaluation of performance of SHP units to ensure smooth evacuation of real power to the neighboring grid as shown in Figure 4.

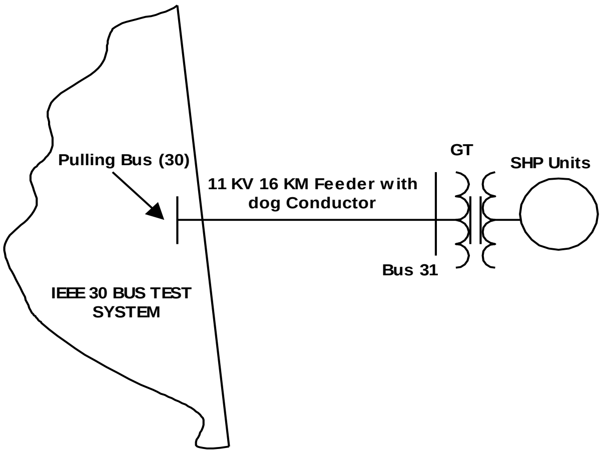

Fig. 4. Location of SHP units in a Grid connected system

The figure shows the bus location (i.e. bus no 30, the weakest bus) at which the SHP units are feeding the power to the IEEE 30-bus test system. In the first step the weakest bus in the IEEE 30 bus test system is identified. Then, a 3 MW SHP unit is connected to the weakest bus with a 16 KM, 11 KV feeder having dog conductors. In the next step, the system load is varied uniformly at all load buses over a wide range, starting from 30% to 125% of base load in order to monitor the voltage status of the evacuation bus. However the focus is made on the extreme loading conditions for monitoring the power evacuation status of the SHP at the weakest bus by studying its generator operation in two modes (Voltage control mode and Power factor mode).

When generators are operated at voltage control mode, it is often observed that for evacuating a small amount of active power huge amount of reactive power becomes necessary in extreme voltage conditions at the pulling bus. This needs a much higher rating generator to supply a small amount of active power. Since the investors get return from KWh generated, it become financially unviable to opt for higher rating machines. This reality makes the operators to prefer power factor control mode of operation. As long as the SHP continues its operation in power factor control mode the exciter control is set for generating the proportionate reactive power in accordance with the active power generated so as to maintain a constant power factor. However, in this mode there is very less scope available with the operators to handle any changes in bus voltages due sudden fluctuations or variation in demand. Therefore, any change in voltage at the pulling bus reflects similar change at the SHP bus. If the voltage variation at SHP bus exceeds the safe limits then there may be additional need for on load tap changing transformer to keep the voltage within safe limits.

The on load tap changing transformer has been installed at the SHP end having tap ratio of ±10% with a step of 1.25%, which provides 17 tapings. The load flow has been carried out with various sets of fixed power factor mode of SHP to observe the possibility of power evacuation under different loading scenario in the grid.

7. Results and Discussion

The simulation results obtained in this work are presented in the following manner. Table 1 indicates percentage change in bus voltage for most affected buses with continuous increase of loads in all buses at the same time. Table 2 shows the L-index of these set of buses under standard base case loading conditions.

Table 1. Buses having higher % voltage change due to simultaneous load increase

Bus No	Loading range in % of base load						% change in voltage
	100	110	120	130	140	150	
24	1.022	1.00	0.98	0.92	0.86	0.757	26
29	1.003	0.98	0.95	0.90	0.83	0.732	27
26	1.000	0.98	0.95	0.89	0.82	0.72	28
30	0.992	0.97	0.94	0.88	0.81	0.707	29

Table 2. L-index for critical buses at base load

Buses with maximum value of L-index and Centroid		
Bus no	L index	Centroid
24	0.104006	0.116099
26	0.120664	0.122211
29	0.122532	0.125066
30	0.143019	0.14409

Table 3. Summary of Critical bus Identification

Bus No	% Change in Bus Voltage at peak loading condition	L index	Centroid	Remark
24	26	0.104006	0.116099	Bus 30 is the most critical bus
26	28	0.120664	0.122211	
29	27	0.122532	0.125066	
30	29	0.143019	0.14409	

Some of the results of Tables 1 and 2 are presented in Table 3, for the sake of simplicity in drawing comparison between these sets of buses in order to identify the most critical bus bar in the system. In Tables 1-3 the results are presented for four buses only, which indicate higher criticality. Out of these four buses, bus-30 indicates highest degree of % change in voltage, L-index and Centroid value, hence considered as the most critical bus in the system.

After identifications of the most critical bus, the SHP units at the external bus (say bus-31) is connected to the weakest bus of the test system (i.e. bus-30) through a 16 KM, 11 KV link and OLTC. The evacuation is observed at extreme voltage conditions with different power factors at the evacuating bus. In order to observe the performance of the power evacuation of the SHP units to the local grid the following extreme conditions are considered. In one case, simulations are carried out at a considerably light loading corresponding to 30% of base case load in the system and the observations are presented in Table 4.

In another case, the simulation is repeated for a significantly higher loading condition that corresponds to 30% rise in loading above the base loads at all the buses. However in both the cases the observation is made for four distinct set of power factors (0.96 lag, 0.98 lag, Unity and 0.96 lead) at which the generators are operating and the corresponding observations are placed in Table 5.

Table 4. Comparison of voltages under light load and constant power factor mode

SHP Generated Power in MW	SHP Power factor	Evacuating Bus Voltage (Bus 30)	SHP Bus Voltage (Bus 31)	Total line loss in MW
1	0.96 lag	1.059	1.059	1.76
2	0.96 lag	1.064	1.064	1.72
3	0.96 lag	1.068	1.068	1.68
1	0.98 lag	1.059	1.058	1.76
2	0.98 lag	1.063	1.062	1.72
3	0.98 lag	1.067	1.066	1.68
1	Unity	1.057	1.057	1.76
2	Unity	1.060	1.060	1.72
3	Unity	1.062	1.062	1.69
1	0.96 lead	1.055	1.055	1.76
2	0.96 lead	1.056	1.056	1.73
3	0.96 lead	1.056	1.056	1.70

Table 5. Comparison of voltages under peak load and constant power factor mode

SHP Generated Power in MW	SHP Power factor	Evacuating Bus Voltage (Bus 30)	SHP Bus Voltage (Bus 31)	Total line loss in MW
1	0.96 lag	0.948	0.948#	27.06
2	0.96 lag	0.955	0.956	26.77
3	0.96 lag	0.962	0.963	26.49
1	0.98 lag	0.948	0.948#	27.06
2	0.98 lag	0.954	0.954	26.78
3	0.98 lag	0.960	0.960	26.51
1	Unity	0.946	0.946#	27.08
2	Unity	0.950	0.950	26.81
3	Unity	0.955	0.955	26.56
1	0.96 lead	0.943	0.943#	27.11
2	0.96 lead	0.945	0.945#	26.86
3	0.96 lead	0.943	0.942#	26.89

It can be observed that, under light load conditions the pulling bus voltage is on higher side (>1.05 p.u.), so evacuation is not possible, as the generator bus voltage violates its safe limit at all generation. However, under over loaded condition, in most cases power evacuation is possible. But the generator voltage is maintained at low voltage (<0.95 p.u.) that causes higher losses.

In order to examine whether the generator can be operated with voltage control mode, the Q limit of the generators are set at very high value for load flow analysis and the corresponding observation are shown in Table 6 and Table 7, corresponding to peak load and light load conditions, respectively.

The result shows that small rated machines when operate with voltage control mode, the MVA rating of the machine become too high which make the promoters not to opt for such high MVA rating machines for economic reasons. Reactive power is managed by on load tap changing transformer connected with the generators. The results of the load flow with OLTC transformer (-10% to 10 %, 1.25% step i.e 16 taps) is given in Table 8.

It is observed that evacuation is possible with the OLTC control but this method suffers from the following drawbacks.

i. Frequent tap changing is needed to evacuate power.
ii. Generator bus voltage is rarely maintained at 1 p.u. (for safer operation).
iii. If the change in system voltage shows faster response, it may be difficult on the part of the operator to decide and actuate the OLTC operation accordingly.

In order to overcome the above difficulties, an SVC is connected at the local bus with a rating of ±10 MVAR, 3.3 KV, 4% slope. The evacuation is observed for all extreme voltage condition. The results are presented in Table 9, which ensures smooth evacuation of the desired real power to the grid.

Table 6. Power requirement in voltage control mode with peak load conditions

SHP Generated Power in MW	SHP Bus Voltage (Bus 31)	Reactive power required in MVAR	Generator MVA required
1 MW	1	6.42	6.497
2 MW	1	5.92	6
3 MW	1	5.44	5.53

Table 7. Power requirement in voltage control mode with light load conditions

SHP Generated Power in MW	SHP Bus Voltage (Bus 31)	Reactive power required in MVAR	Generator MVA required
1 MW	1	-7.55	7.616
2 MW	1	-7.9	7.963
3 MW	1	-8.23	8.29

Table 8. Bus voltages with constant power factor mode and OLTC control

SHP Generated Power in MW	SHP Power factor	Evacuating Bus Voltage (Bus 30)	SHP Bus Voltage (Bus 31)	Optimal tap position of OLTC Transformer
1	0.96	1.054	1.006	-5%
2	0.96	1.054	1.011	-5%
3	0.96	1.054	1.002	-6.25%
1	0.96	0.941	1.008	+6.25%
2	0.96	0.941	1.003	+5%
3	0.96	0.941	1.011	+5%
1	Unity	1.054	1.004	+5%
2	Unity	1.054	1.007	+5%
3	Unity	1.054	1.009	+5%
1	Unity	0.941	1.005	+6.25%
2	Unity	0.941	1.01	+6.25%
3	Unity	0.941	1.002	+5%

Table 9. Comparison of voltages for constant power factor mode and SVC control

SHP Generated Power in MW	SHP Power factor	Evacuating Bus Voltage (Bus 30)	SHP Bus Voltage (Bus 31)	MVAR supplied by the SVC
1	0.96	1.054	1.003	-7.45
2	0.96	1.054	1.003	-8.05
3	0.96	1.054	1.003	-8.65
1	0.96	0.941	1.000	6.09
2	0.96	0.941	1.000	5.33
3	0.96	0.941	1.000	4.59
1	Unity	1.054	1.003	-7.17
2	Unity	1.054	1.003	-7.5
3	Unity	1.054	1.003	-7.82
1	Unity	0.941	1.001	6.37
2	Unity	0.941	1.000	5.89
3	Unity	0.941	1.000	5.43

8. Results and Discussion

The main focus of this paper is to ensure smooth evacuation of real power generated by SHP units to the neighboring grid. While dealing such issues, the practical limitations faced by such units have been considered carefully in this work. Among few major issues, the two most important operational issues such as (i) operation in constant power factor mode and (ii) operation in voltage control mode have been well addressed in the paper. During the simulation of the case study it is observed that the existing control mechanisms of SHP units (i.e. exciter control and OLTC transformer control) exhibit limited scope of real power evacuation to the grid. In order to overcome this difficulty, the authors have attempted the application of SVC control mechanism and the corresponding results are found to be very much satisfactory. From the above results it is inferred that the application of SVC control in SHP units could provide a viable option for ensuring smooth and secure evacuation of real power to the grid.

Acknowledgements

The authors are extremely thankful to the authorities of Neora Hydro Limited, West Bengal, India for their cooperation in allowing the authors to conduct a practical study on the limitations faced by the SHP units at Neora while a part of the study concerning to OLTC transformer control was carried out successfully.

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