Improvement of Voltage Stability due to Integration of the Celukan Bawang Power Station to the Bali 16-bus System

by I Made Wartana

Improvement of Voltage Stability due to Integration of the Celukan Bawang Power Station to the Bali 16-bus System

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***Abstract*—A significant power system occurrence, the voltage stability of the system due to the integration of new generation into the grid, has been investigated in this paper by using a continuous power flow (CPF) method consisting of successive load flows. Since one of the solutions to prevent voltage instability causing voltage collapse is by controlling the system's reactive power limit, in this study the effect of placing the Shunt FACTS controller, Static Var Compensator (SVC), into the grid against the voltage stability has been investigated. An accurate controller model supported by the PSAT (Power System Analysis Tool) is used to study the voltage stability of the system. The effectiveness of the proposed method has been examined on the 16-bus Bali practical test system due to the integration of the Celukan Bawang Power Station and by detecting the bifurcation point. Moreover, improving voltage magnitude profile and line power loss (Ploss) of the system are also investigated.**

***Index Terms*—Continuation Power Flow; SVC; Voltage Stability; Voltage Collapse.**

I. Introduction

Over the last few decades, one of the most important issues of the electric power industry is the voltage collapse of the power system which is the main cause of some power outages in some parts of the world. In the report [1], it has examined the direct connection between saddle-node bifurcation and voltage collapse. Whereas the direct and continuous methods by which the continuous power flow method is used for voltage analysis have also been developed and applied on the basis of bifurcation theory about the calculation of collapse points [2]. The point of voltage collapse when the Jacobian-related power flow becomes single which is the identification of the equilibrium point of the system involved in this technique [3].

The voltage instability condition can lead to system voltage collapse which can further deteriorate the system voltage to a level where the system cannot be recovered. [4]. Of course, this condition causes a partial or full power failure on the system when the system is loaded beyond its maximum limit. By reducing the reactive power load or adding additional reactive power before it reaches the point of voltage collapse is one method to save the system [5], [6]. Installing one type the sources of reactive power, i.e., shunt Flexible AC Transmission System (FACTS) controllers at the appropriate location is the most effective way for utilities to enhance the voltage stability of the system [7].

FACTS controllers is a recent development in power transmission system have led to many applications [8]. These controllers are not only to improve the voltage stability of the existing power network resources but also to provide operating flexibility to the power system. There are five well-known FACTS devices utilized by the utilities and each of them has its own characteristics and limitations. One type of shunt FACTS controller, Static Var Compensator (SVC), is used for this purpose, which is possible to achieve voltage stability criteria. An application of Artificial Bee Colony (ABC) in optimizing the rating of SVC for voltage stability augmentation in power system is presented in [9]. Al-Mubarak and M. H. Khan proposed Dynamic Reactive Power Compensation to provide reactive power support during different network disturbances and accelerate the voltage recovery process using SVC. Voltage Stability under load scenario using STATCOM is studied in [10]. Applying saddle-node bifurcation theory with the use of Power System Analysis Toolbox (PSAT) by the optimal location of STATCOM and UPFC Controllers is determined [11]. Also in [12], a static voltage stability using four different type FACTS devices have been evaluated by CPF method.

Work done in the literature so far, nothing has been proposed about the effect of static voltage stability by using CPF due to the integration of new generations into the grid. In addition, the effect of FACTS device placement is not only on voltage stability but also on voltage profile, and line power loss needs to be involved. This paper considers the use of one type of Shunt FACTS controller, SVC, to improve the loadability margin of the power system after integration of new generation into the grid. Appropriate representations include the equations in the DC portion of FACTS devices incorporated in the CPF process in a static voltage stability study. Based on the above observations, the effort made in this paper is to analyze the impact of the installation of Shunt FACTS device, SVC, in the case of Maximum Loading Point (MLP) in a static voltage stability study after the integration of the new plant and by taking into account the voltage profile and loss of transmission lines.

II. Problem Formulation

A. System Modelling

The proposed method is performed on Bali's 16-bus practical test system which is modeled on the PSAT Power Station that has many features including power flow, and continuous power flow (CPF) used for voltage stability analysis. The practical test system shown in Figure 1 contains 16 buses, 31 lines, and 4 generators, whereas the new generation Celukan Bawang consists of three power plants, totaling 380 MW, integrated into the grid since 2015. The total system generating capacity is 962 MW, and 15 load buses, 976.45 MW and 230.46 MVAr, real and reactive power load respectively [13].

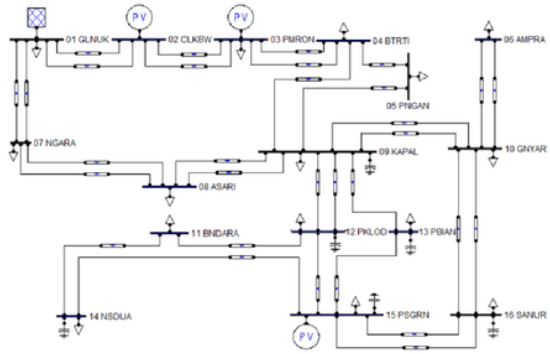

Figure 1: Single line diagram of Bali 16-bus practical test system.

B. Shunt FACTS modeling

To control the reactive power in the system in an exertion to improve the system loadability, one type of shunt FACTS controller known as SVC is used in this study. This controller not only has thyristor controlled switched reactor (TSR) but also thyristor switched capacitor (TSC) to absorb and inject the reactive power, respectively which is modeled as an ideal reactive power injection at bus i [14].

The reactive power injected at the SVC node is expressed in the algebraic Equation (1) and (2) [15], [16]:

$$\Delta Q_i = Q_{SVC} \tag{1}$$

$$Q_{SVC} = b_{SVC} V^2 \tag{2}$$

where V and b_{SVC} are the voltage magnitude of a bus at which the component is connected and total reactance of the controller, respectively.

C. Voltage Stability Analysis

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. In heavy-loaded systems that do not have sufficient local reactive resources, a voltage collapse may occur which results in a secure voltage profile for the system unattainable. The shortage can be relieved by optimal placement of FACTS Controller in the systems to improve voltage stability [17]. In this paper, the placement of one type of Shunt FACTS (SVC) controller, to the grid that has been integrated with the new generation, is able to inject reactive power quickly and dynamically, thus being used by system operators to improve system security and stability. By placing the SVC in the best location, it can increase the voltage stability, then it is necessary to identify the most suitable bus for the installation of the controller. The stability of the system can be studied by means of the well-known bifurcation diagrams. These diagrams are built by computing the equilibrium points of the system as one parameter varies, and then plotting any state variable as a function of that parameter [18].

D. Total Power Losses

The total real power loss in a power system is shown in (3) [19].

$$P_{loss}(\mathbf{x},\mathbf{u}) = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right] \tag{3}$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j) \quad ; \quad \beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin(\delta_i - \delta_j)$$

$V_i\angle\delta_i$ = complex voltage at the bus i^{th};
$r_{ij} + jx_{ij} = Z_{ij}$ = ij^{th} element of $[Z_{bus}]$ impedance matrix;
P_i *and* P_j = active power injections at the i^{th} *and* j^{th} buses, respectively;
Q_i *and* Q_j = reactive power injections at the i^{th} *and* j^{th} buses, respectively;
N = number of buses.

III. Methodology Development

The CPF function included in PSAT is a novelty among available Matlab-based packages for power system analysis. The CPF algorithm consists of a predictor step which computes a normalized tangent vector and a corrector step that can be obtained either by means of a local parametrization or a perpendicular intersection [20]. One of the most important problems in the analysis of voltage stability that cannot be calculated directly using modal analysis is the determination of the maximum loading. Taking into account the loading scenario, in addition to calculating the voltage profile to the point of collapse, where the Jacobian matrix becomes single, also to determine the voltage security limit (VSM) then the CPF applies the solution in sequence. Whereas, the VSM is the distance from the operating point to the point of collapse of the voltage. The power at the loads continues to increase by scaling factors in the successive procedures, such as:

$$P_L = P_{L0} + \lambda P_D \tag{4}$$

$$Q_L = Q_{L0} + \lambda Q_D \tag{5}$$

where P_{L0} and Q_{L0} are load active and reactive powers of the base case whereas P_D and Q_D are the load power direction. In each generator, scaling factors can be easily used to measure the power generated or may be limited by the constraints.

IV. Result and Discussion

The simulation to examine the method in solving the improvement of voltage stability has been done on Bali 16-bus practical test system which is discussed in the previous section. To investigate the voltage stability of the practical test system is used CPF, one of the features on the PSAT, and simulated in two scenarios: scenario-1, base case (without SVC) and scenario-2 where the result in the first scenario is compared with those under different loading conditions with SVC that is represented 3 lowest voltage buses, respectively. By bifurcation analysis, the appropriate location of the SVC controller is determined, regardless of the typical PQ model used for load and generator limits. While the voltage stability analysis is done by increasing the load using the λ factor until it reaches a single point of flow that previously started from the initial stable operating point.

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A. *Scenario-1: base case (without SVC)*

Figure 2 indicates that the CPF results for 3 buses in the base case condition viz.: bus -5 PNGAN, bus-7 NGARA, and bus-8 ASARI are 3 lowest voltages. In this scenario, when the Jacobian matrix system reaches singular at $\lambda_{max.} = 2.5611$, this means that this system has presented its maximum loading or a collapse points. As depicted in Figure 3, the bus-8 has the weakest voltage profile of 0.77 p.u. when compared to other buses. Based on Figure 1, 2 and 3, the 3 buses are indicated as the lowest voltages which needing Q support.

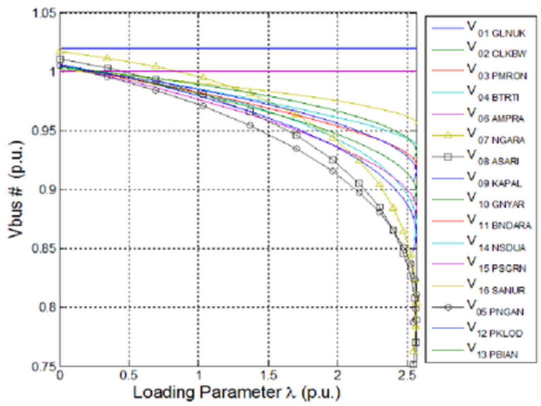

Figure 2: PV curves of Bali 16-bus practical test system at the base case with plot 3 lowest voltages

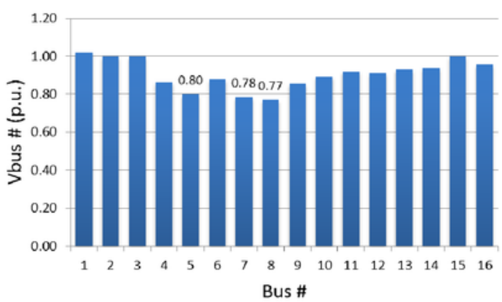

Figure 3: Voltage magnitude profile of Bali 16-bus practical test system at base case

B. *Scenario-2: with SVC on 3 lowest voltage buses*

Based on the collapse analysis as described in Figure 2 and 3, bus-8 ASARI was chosen as the first location for SVC controller, since this bus is the weakest bus. Figure 4 depicted the PV curves of the practical test system when the SVC is installed at the desired bus where the new maximum loading level under this scenario increase up to $\lambda_{max.} = 2.6454$ p.u. Moreover, under these conditions, there is no limit to the minimum voltage violation as shown in the magnitude voltage profile as shown in Figure 5.

When the same SVC mounted on the bus that is not a critical voltage bus, this condition indicates that the maximum load limit does not change too much. For example, since the controller is installed on the bus-7 NGARA its $\lambda_{max.}$ slightly up to 2,6513 p.u., even on the bus-5 PNGAN, λ_{max} simply dropped to 2.6353 p.u. as where their PV curves are represented in Figures 6 and 8, respectively. On the other hand, in these cases, both of the conditions have voltage limit violation as depicted in Figure 7 and 9. Whereas Table 1 presents the CPF result for the two scenarios. From Table 1 it can be observed as well that, placement of SVC in bus 8 provides the lowest SVC setting and line power loss (P_{loss}) of the system, 1,3219 p.u. and 971.38 MW, respectively.

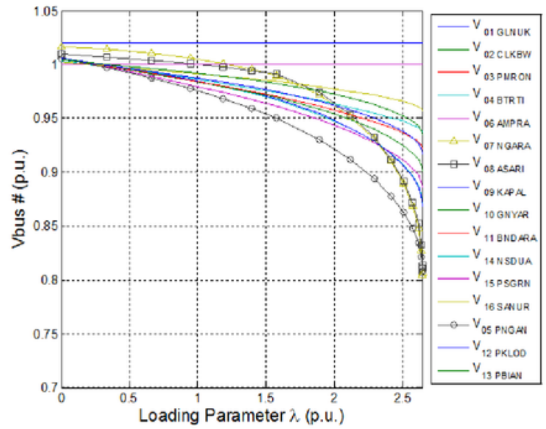

Figure 4: PV curves of Bali 16-bus practical test system with SVC at bus 8 and the plot 3 lowest voltages

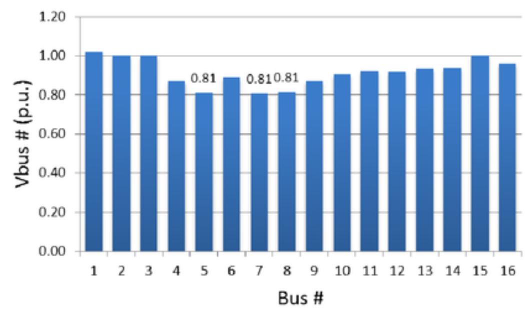

Figure 5: Voltage Magnitude Profile of Bali 16-bus practical test system with SVC at bus 8.

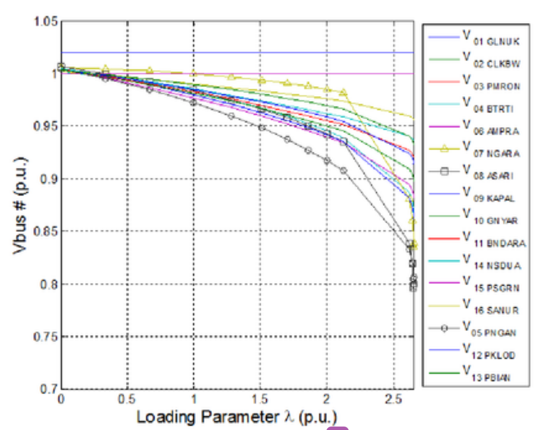

Figure 6: PV curves of Bali 16-bus practical test system with SVC at bus 7 and the plot 3 lowest voltages.

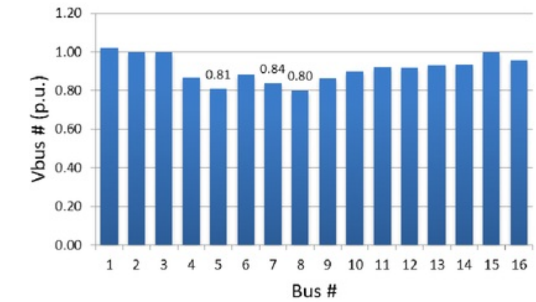

Figure 7: Voltage Magnitude Profile of Bali 16-bus practical test system with SVC at bus 7.

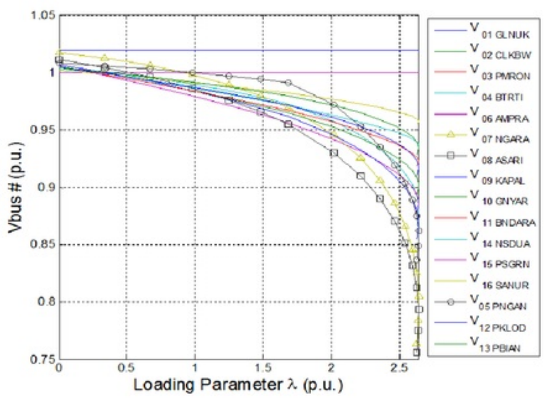

Figure 8: PV curves of Bali 16-bus practical test system with SVC at bus 7 and the plot 3 lowest voltages.

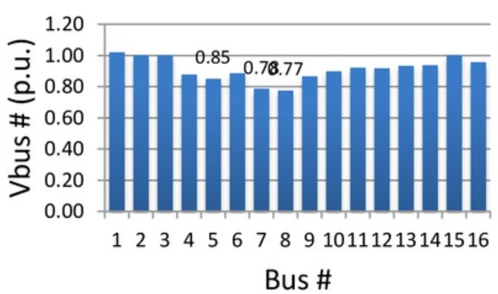

Figure 9: Voltage Magnitude Profile of Bali 16-bus practical test system with SVC at bus 5.

Table 1
The CPF Result for two Scenarios

Scenario	Location (bus)	Setting (p.u.)	λ (p.u.)	Voltage violation (bus)	P_{loss} (MW)
1 (base case)	-	-	2.5611	5,7, and 8	1021.41
2 (3 critical bases)	5	1.4421	2.6353	7 and 8	2573.25
	7	1.4016	2.6513	8	968.64
	8	1.3219	2.6454	-	971.38

V. CONCLUSION

Valuation of voltage stability on the Bali 16-bus practical test system by using one type of shunt FACTS device, SVC, has been investigated in this paper. The SVC can improve voltage stability margin due to the integration of the Celukan Bawang Power Station to the Bali 16-bus practical test system. The practical test system requires reactive power the most at the weakest bus. Introducing reactive power at this bus using SVC can improve voltage magnitude profile and line power loss (P_{loss}) of the system. Using CPF method, it was found that this FACTS controller significantly enhances the performance of power systems by placement of the controller in the proper load bus among 3 lowest voltages.

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