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Dynamic Voltage Signature of Large Scale PV Enriched Stressed Power System

Saeed Alzahrani, *Student Member, IEEE*, Rakibuzzaman Shah, *Member, IEEE*, N. Mithulananthan, *Senior Member, IEEE*, and Arthit Sode-Yome, *Senior Member, IEEE*

Abstract— Renewable power generations including flexible demand and energy storage systems leverage significant changes in network operation. Thereby, power systems with high renewable penetration manifest deteriorated resilience to disturbances. Hence, the stable operation of the system could be affected. With a paradigm shift, dynamic voltage stability becomes one of the major concerns for the transmission system operators (TSOs). Predicting the dynamic voltage signature for the transmission system with high penetration of renewables is essential to assist in selecting appropriate corrective control. This paper utilized a comprehensive assessment framework to identify the dynamic voltage signature of the power system with PV and various loads. The voltage recovery index has been chosen as the quantifiable index to extricate the dynamic voltage signature. The applicability of the proposed framework is discussed using simulation studies on the IEEE-39 bus test system.

Keywords— Correlation, dynamic voltage signature, PV, voltage recovery index, voltage stability.

I. INTRODUCTION

A. Motivation

With renewable energy penetration and fierce market competition in power grids, electric power networks are often required to operate close to their limits, significantly increasing the risk of instability. In the modern power system, stability is only determined by the physical characteristics of synchronous generators (SGs) but increasingly depends on the complex control of renewable generation, range of system operating conditions, grid code set by the transmission system operators (TSOs) [1].

With a paradigm shift in power generation that resulted in the retirement of SGs, voltage stability becomes one of the significant issues for the transmission system operators (TSOs) around the world. The SGs in the system is the primary resource for steady-state and dynamic reactive power reserves [2]. The significant replacement of SGs with a converter based generator with limited reactive power reserve compared to SGs may cause the voltage depression and fault induced delayed voltage recovery. Moreover, the primary focus of the converter based generations is to meet the fault-ride through the generator rather than the stability of the network. Therefore, the renewable rich power system manifests the weakened resilience to the voltage disturbances.

Different classification techniques (i.e. decision tree, support vector machine) can be applied to convert PMU data into dynamic information and real-time decision making. The prediction typically defines whether the system is the stable or goes to the unstable region after the disturbances. When the system goes unstable region, the system can be grouped into different subsystems based on similar dynamic behaviour i.e. dynamic signature. The dynamic signature of the system is more likely to be predicted to assist in selecting the corrective

measures. Relatively a new concept referred to as a power system dynamic signature has been explored for rotor angle stability. Although the scope of these studies is quite relevant to work in [3], this work approach towards the dynamic signature of the system concerning voltage stability.

B. Literature Review

Several research papers have reported the dynamic voltage stability issue by considering load dynamic and dynamic VAR compensation [4]-[6]. Despite there being many works (many others not mentioned for brevity) regarding voltage stability assessment and corrective measures, very few reported the post fault dynamic voltage signature. Most importantly, the dynamic voltage signature and interdependency of different dynamic behaviour would help in decision making with the most effective post-fault strategy for reactive power deployment.

Due to the brevity, only PV generation has been considered in this work. A comprehensive model of transmission connected large scale PV system for dynamic voltage stability is used in this work. Numerous research works have been reported the different modes of reactive power control for PV, i.e. voltage control, power factor control, and reactive power control [4]. Since the large power plant is required to control the voltage and/or reactive power at the point of common coupling, this paper has focused on the voltage and reactive power control schemes with associated limits and dead-band. The secondary voltage control concept, which eliminates the voltage error, has not been considered in this work.

The main focus of this study is to investigate the influence of non-synchronous PV generator on the dynamic voltage stability and identify the importance they have on the dynamic voltage signature of the system. The factors that influence the dynamic signature are identified, and their influences are quantified using appropriate indices. The remainder of the paper is organized as follows: Section II presents the system model and simulation scenarios with background on indices for dynamic assessment. The steady-state and dynamic assessment results are presented in Section III and IV. Finally, the conclusions and future works are highlighted in Section V.

II. MODELLING OVERVIEW

A. Test Power System

The 10-machines 39 bus New-England power system, widely known as the IEEE 39 bus test system is used as the test system in this research [7]. A modification has been made to examine the impact of large-scale PV (LSPV) power plants on the dynamic reactive power capability (DVAR) of a stressed grid. The modification has been made to integrate LSPVs at some high voltage buses (345 kV) with conventional power plants as depicted in Fig. 1.

Several simulation scenarios have been considered to realize the primary goal of this research. The impact of retiring SGs in the grid is examined by reducing the MVA rating of SGs and replaced retired SGs by LSPV units with the same MVA. The impact of high PV penetration is also examined with high reactive power demand on the system. In all scenarios, the consequence of VAR demand increment is also considered by increasing the reactive power demand from 100-130% with a 5% incremental step. It has been assumed that the increase in loads active power would be supplied by locally distributed generators such as rooftop PV units where the grid code does not require them to generate reactive power [8]. Table I shows the simulation scenarios, including the penetration levels and active and reactive power limits of LSPV systems.

Fig. 1. IEEE 39 bus test system [7].

TABLE I. PV PENETRATION SCENARIOS

Scenarios #	SG -MVA %	PV- MVA %	PV-P %	PV- Q %
1	100	0	0	0
2	100	5	6	9-6
3	95	5	6	9-6
4	90	10	12	18-13
5	85	15	19	28-19
6	80	20	25	38-26
7	75	25	31	48-33
8	70	30	37	58-40

B. Load & Generator Model

In this study, the loads are modelled as voltage-dependent loads. The static part of the load model used in this work is represented by an exponential load model as given in (1).

$$P = P_0 \left(\frac{V}{V_0} \right)^\alpha, Q = Q_0 \left(\frac{V}{V_0} \right)^\beta \quad (1)$$

In (1), P and Q are the active and reactive power consumed by the load at V bus voltage. P_0 and Q_0 are the active and reactive power demand at V_0 reference voltage. The exponential parameters (α) and (β) will be used as a sensitivity factor of the load power to the load bus voltage variation. Moreover, the load will be considered as constant power, constant current or constant impedance if for the exponential parameters value are chosen to be 0, 1 or 2 accordingly.

The following active and reactive power relationship for the dynamic load model developed in DigSILENT PowerFactory has been used [9]. In this model, the real and reactive power consumptions are given by (2) and (3), respectively.

$$\Delta P = \frac{K_P + t_P s}{1 + T s} \Delta V \quad (2)$$

$$\Delta Q = \frac{K_Q + t_Q s}{1 + T s} \Delta V \quad (3)$$

In (2) and (3), K_P and K_Q are the voltage dependent index, t_P and t_Q are the voltage time constant, and T is the dynamic load constant.

The SGs are modelled with their sub transient parameters. The SG2 to SG10 are equipped with IEEE Type 1 automatic voltage regulator (AVR). Speed governor (GOV) is also installed on SG2 to SG10. Steam turbine governor IEEE Type G1 is used for SG 2-9. Generator SG 10 is equipped with a hydro turbine governor i.e. IEEE Type G3. The transmission lines are modelled with the standard π equivalent circuit. The WECC large-scale PV plant model with Electrical Control Model (REEC_B) and the Generator-Converter Model (REGC_A) is used in this work [9], [10].

C. LSPV Control Mode

Based on the grid code, the LSPV system should support system voltage by injecting or absorbing reactive power at the point of common coupling (PCC) [8], [11], [12]. This can be achieved by operating the PV inverters in voltage or reactive power control modes [13], [14]. Other approaches can be used where STATCOM or synchronous condenser can be installed at the PCC, and operating the PV inverters at unity power factor or operate them all together in a coordinating fashion [15]. However, more investigations still need to be done to see if those approaches of additional VAR systems at LSPV side in the form of STATCOM or Synchronous Compensator are economically feasible.

1) Voltage Control Mode

In the voltage control mode (VC), the plant controller will work to attain the PCC set voltage. This can be achieved by assigning the required VAR among the PV inverters.

2) Reactive Power (VAR) Control Mode

In the reactive power control mode (Q), the LSPV plant provides or absorbs a certain amount of reactive power at the PCC regardless of the PCC voltage profile. The required VAR would be shared among the PV inverters.

Different d and q axis current limits can be applied to the converter based generator. A fixed d and q current limit have been used. In this current limit, the concept comprises of fixed current limit. This means that the converter system will remain connected to the system without injecting any additional reactive current. This is the widely used current limit logic in literature. Three different current priorities can be used for such current limit logic. These can be-

- Active and reactive current has equal priority.
- Active current has higher priority than reactive current.
- Reactive current has higher priority than reactive current.

While designing the fixed current limiter in this paper, active current is prioritized in the outputs of the current magnitude.

The fixed current limit with reactive current priority can be defined by (4) [4].

$$i_d^* = \max(i_{lim}^*, i_{dref}^*), i_q^* = \max(\sqrt{i_{lim}^{*2} - i_d^{*2}}, i_{qref}^*) \quad (4)$$

D. Indices for Dynamic Assessment

This section briefly explains the quantitative indices used to examine the dynamic signature concerning voltage stability. For a renewable rich network with high penetration of induction motor loads, a voltage recovery performance of the load bus is a crucial aspect of voltage stability [16]. Several indices can be used to evaluate the voltage recovery, such as Voltage Deviation Index (VDI), Improved Voltage Stability Index (IVSI), and Voltage Stability Factor (VSF), and others [17]. In this research, a recently developed voltage recovery index (VRI) [4] has been used. Moreover, the synchronous generator area of influence has been employed to link the voltage recovery performance of each load bus with the dynamic VAR reserve (DVAR). The combination of these two may help size the LSPV plant (optimal size), location for VAR resources, and the optimal tuning of the coordinated control of the LSPV and other VAR resources. In this study, the dynamic performance of the system is explored by applying a three-phase short circuit at load buses. The faults are cleared after 100 ms, and the voltage profiles are recorded for 5 seconds after the faults.

1) Voltage Recovery Index

Lammert *et al.*, [4] had investigated the phenomenon of the fault-induced delayed voltage recovery (FIDVR) and a voltage recovery index (VRI). The VRI is a useful index that can be used to investigate the short-term voltage stability issue and other concerns related to the optimal control approaches of grid-connected inverter-based resources. VRI uses the grid code such as the WECC criterion given in [18] as a reference to benchmark the transient voltage behaviour of the load bus as in Fig. 2. The VRI can result in a value between 1 and -1, where one means the bus voltage returns to its pre-fault value within the required time. On the other hand, -1 means the bus voltage does not recover at all. If VRI equals to zero, it means the transient voltage of the load bus meets the minimum requirements of the grid code. The following pseudocode briefly outlined the main steps in calculating the voltage recovery of the load bus [4].

- Step 1: Define the voltage violation criteria.
- Step 2: Partition the voltage between V_{max} and V_{min} into L sub-intervals. This partitions are known as samples.
- Step 3: Define the probability density function p^{VRI+} & p^{VRI-} of the voltage samples.
- Step 4: Define and apply the weighting function to reward (η_j^+) or penalise (η_j^-) the voltage recovery.
- Step 5: Calculate the voltage recovery index (VRI) of the load bus according to (5), where A denotes the total number of the voltage samples, M expresses the numbers of voltage constraints.

$$VRI = \frac{1}{A} \sum_{j=1}^M \sum_{i=1}^L (\eta_{ji}^+ p_{ji}^{VRI+} + \eta_{ji}^- p_{ji}^{VRI-}) \quad (5)$$

2) Area of SG Influence

An area of influence of each SG has been used to explain better the effect of the DVAR reserve on the voltage recovery. For a large and interconnected power system, not all the SGs have the same influence on the load buses voltage recovery. Therefore, an idea of looking to the effect of SG outage on the

short circuit level (SC) of each load bus has been used to examine the impact of the synchronous machine DVAR reserve on the load voltage recovery.

Fig. 2. Voltage recovery index VRI and WECC Criterion for voltage recovery [4].

The SC level at each load bus mainly depends on the rating of the SG and the electrical distance between the fault current source and the fault sink. For a mesh network, when a fault occurs in any load bus, the system SGs and other fault current sources would be aware of the fault incident in different degrees based on the electrical distance from that fault. Accordingly, different fault current contributions from generators would flow in a mesh network. In the base case (with all SGs), each bus has its specific short circuit level Bus_{ioldSC} which would drop after an outage of SG_j to a new value Bus_{inewSC} . Then, the percentage of change in the bus SC level is multiplied by $SG_j_MVA_{norm}$ which represents the weighted MVA level of the SG_j . Hence, the system SGs have different MVA ratings. Therefore, the load bus SC sensitivity (Bus_iSCS_j) can be found by using (6).

$$Bus_iSCS_j = SG_j_MVA_{norm} \left(1 - \frac{Bus_{inewSC}}{Bus_{ioldSC}} \right) \quad (6)$$

III. STEADY-STATE ASSESSMENT

The steady-state performance of a power system with high penetration of LSPV and demand for reactive power has been carried out here. In the steady-state assessment, the impact on load bus's short circuit level and the SG active and reactive power operating limits and trends are explored to link the DVAR to the dynamic voltage profile of the load buses.

A. System Short Circuit Level

System strength is one of the critical aspects that must be considered carefully in the current and future power systems. The amount of the short circuit current that can be injected during the disturbance is significantly effected in a stressed and renewable rich network. Fig. 3 shows the changes in the short circuit level of the load buses in the test system for the simulation scenarios given in Table I. Even though the load buses have different levels of the fault current, the influence of PV penetration on the fault current is almost homogenously distributed among those load buses. Having been said that the dynamic VAR profile of those load buses needs to be explored under different levels of uncertainty. Therefore, in the following sections, the transient response of the load buses

will be examined under different scenarios in a stressed and renewable rich power system.

Fig. 3. Load bus short circuit MVA level.

B. Generator's Operational Range

Figure 4 shows the SGs active power output ranges during the scenarios given in Table I. Among the SGs, SG 3-9 are operating close to their maximum active power limits while SG 10 is 40% loaded. The reference bus machine (i.e. SG – 2) has a wide range of operating points. When the MVA ratings of SGs are reduced, their maximum active power is also reduced. However, the active power reduction from SGs is compensated by the active power generated by the LSPVs integrated throughout the test system.

The SGs and LSPV dynamic reactive power (DVAR) capabilities are the interest in this investigation. After any disturbance in the system, the quality of the voltage recovery is highly influenced by the system DVAR. Similar to the active power, the SG has a limited capability in providing DVAR to the system under lower MVA rating. Fig. 5 displays the operation range of the SGs in terms of their reactive power. From that figure, SGs can be classified into three groups in terms of the DVAR reserve availability. The first group (which includes SG 2, SG 3, SG 5, and SG 6) has a low-level VAR reserve and operating close to their max reactive power limits. The second group (which includes SG 4, SG 7, and SG10) is almost loaded half in terms of the VAR generation, and this group can be classified as a mid-level VAR reserve. The third group of SGs is slightly loaded, and there is a sufficient VAR reserve at these machines. That group includes SG 8 and SG 9. This group can be categorized as a high-level VAR reserve group.

Fig. 4. Generators active power operation range.

The SGs in the system exhibit different operation trends when more LSPV plants are integrated into the system, and VAR demand increased at the load buses. Fig. 6 illustrates the SG's reactive power trends for the given simulation scenarios.

These SGs exhibit certain patterns; for example, SG 8 & SG 9 have the highest rate of variation for the given simulation scenarios. More investigations need to be done to account for the factors that affect the SG operational range and trends when more renewables are integrated and under different loading conditions.

Fig. 5. Generators reactive power operation range.

Fig. 6. Generators VAr trend with more PV and VAr demand.

IV. DYNAMIC ASSESSMENT RESULTS

The dynamic performance of the system is the core interest of this research. With the help of the steady-state assessment outcomes, the system response during the transient would be interpreted from the viewpoint of the DVAR reserve by using the VRI and the SG area of influence.

A. SG Area of Influence

The area of influence of each generation unit on the load buses has been used to identify the most dominant machine influencing the transient response of that bus. With the outage of each SG, the reduction on the load bus short circuit level is presented in Table II. After that, the dominant SG of each load bus can be chosen based on the SC sensitivity's highest value. For example, the outage of SG 02 would reduce the short circuit level at bus 03 by 4%. On the other hand, if SG 10 is taken out of service, the short circuit level at bus 03 is reduced by 17%. Hence, SG 10 outage represents the largest short circuit sensitivity of bus 03, SG 10 is considered as the most influential machine on that bus. A similar SC sensitivity analysis can be carried for all the load buses and presented in Table II.

It can be noticed that some load buses have very high sensitivity with respect to the outage of a particular machine such as Bus 29 to SG09. Other machine outages may have a limited impact on bus 29. Moreover, some load buses may influence by more than one machine such as buses 15, 16, 18, and 24. For simplicity, the most influential machine

corresponding to each load bus with the highest sensitivity value is given in Table III. The VAr operational range of SGs and trends can be used to categorize the load bus in terms of the availability of the DVar reserve. For instance, Buses 26-29 are affected by SG 8 or SG 9 where both of the machines have a high DVar reserve. Later on, the classification of those buses based on the area of influence and DVar reserve can be judged by using the outcome of the VRI under different operating ranges.

TABLE II. AREA OF INFLUENCE (%) OF THE SGs

Load Bus	G 02	G 03	G 04	G 05	G 06	G 07	G 08	G 09	G 10
3	4	5	2	1	3	2	6	4	17
4	9	11	3	1	3	2	3	3	8
7	12	11	2	2	2	2	3	3	5
8	12	11	2	2	2	2	3	3	5
15	3	5	5	2	6	4	2	3	4
16	2	3	9	4	10	6	2	4	5
18	3	3	3	2	4	3	4	5	11
21	1	2	4	2	15	8	1	2	2
23	1	1	2	1	18	18	1	1	1
24	2	2	6	3	9	7	2	3	4
25	2	2	1	1	1	1	17	7	22
26	1	1	1	1	2	1	6	22	9
27	1	2	2	1	3	2	4	13	7
28	0	0	0	0	0	0	2	37	3
29	0	0	0	0	0	0	2	48	3

TABLE III. VAR RESERVE AND SG AREA OF INFLUENCE

VAr Reserve	SG	Load bus within the Area of Influence
Low	2,3,4,5 & 6	4,7,8,15,16,21 & 24
Mid	4,7&10	3,18 & 23,25
High	8&9	26,27,28 & 29

B. Voltage Recovery Index (VRI)

The VRI has been used to measure the dynamic responses under all operating scenarios. As an example, the VRIs of load at bus 16 (randomly chosen) are presented in Fig. 7. It is clear that the PV penetration levels have a significant influence on the VRI of the selected bus. At the base case without LSPV, the VRI is 0.976, while the VRI has reduced by 1.2 % under 30% LSPV penetration. The impact of PV penetration does not have a linear relationship with VRI. Each bus has its dynamic signature that could be inflated by PV in non-linearly. From Fig. 7, it can be seen that 15 % PV results in the optimal VRI. It also indicates that there is a limit at each bus and that the response could be reduced significantly beyond that limit. The loading conditions may have an effect on the bus VRI. A high VAr demand shows a positive impact on the VRI, where 0.79 % improvement can be achieved when VAr demand is increased by 30% from the base case. Moreover, the VAr growth under different PV penetration levels can slightly improve the VRI. Other load buses in the system may exhibit different VRI performances, and the influence of LSPV power plant penetration, as well as the VAr demand, are depicted in Fig. 7.

The VRI results can easily be justified with the help of the SG area of influence given in Table II and Table III. The load

buses that are influenced by SG with a high DVar reserve may improve the VRI with more PV penetration. On the other hand, low DVar reserves in SG could affect the load bus within their area of influence. Therefore, the VRI of these buses would be reduced with the increment of PV penetration levels. Even though bus 27 was considered to be within the area of influence of high DVar reserve, the VRI of bus 27 is reduced when more LSPV. This could happen due to the influence of low and medium DVar reserve on bus 27, and their accumulated influences are stronger than the high DVar reserve generator. Generally, the availability of the DVar reserve enhance the system dynamic performance even though more inverter-based resources being connected into the grid.

Fig. 7. Voltage recovery index (VRI) of bus # 16.

C. PV Control Methods Impacts on VRI

This research has also examined the influence of the LSPV control strategies on the dynamic voltage profile using VRI as a measuring tool. The voltage control method and the reactive power control method have been used for all simulation scenarios. Generally, PV plants operated either on voltage control mode (VC) or constant reactive power mode control methods (CQ) could have a similar trend of the system's short-term voltage stability. Fig. 8 demonstrates the percentage of variation VRIs in the load buses for the 30% PV compared to the base case (i.e. without PV penetration). Increasing the PV penetration may have an adverse impact on the voltage recovery of the most load buses. For example, when 30% of SGs are replaced by LSPV plants, the VRI at bus 8 (randomly chosen) is reduced by 4.25% (for the CQ mode, the reduction is 3.25%). On the other hand, the voltage recovery of a few load buses (i.e. bus 26, 28, and 29) is enhanced when more PV plants are integrated into the system. For example, the VRI at Bus 29 is improved by about 25-30% when LSPVs replace 30 % of SGs in the system.

Among the two control methods of LSPV plant, voltage control may show a better performance slightly for the load buses located within the area of influence of low and medium DVar reserve, as given in Fig. 8. For such a situation, the voltage control method of the PV system may reduce the stress on the SGs, as depicted in Fig. 9. Therefore, more DVar can be supplied during system disturbances that could improve the system recovery. On the other hand, the constant reactive power mode control method shows a superior consequence for the load buses within the area of influence of SGs with high DVar reserve, i.e. bus 26, bus 28, and bus 29. Tuning of PV control methods could affect the dynamic system performance of each load bus where the optimal voltage set-point and the optimal power factor need to be examined carefully in future research.

Fig. 8 VRI variations of different control methods of the PV system.

Fig. 9 SGs-VAr operation range for different PV control modes.

V. CONCLUSIONS

This study has explored the dynamic voltage stability of stressed and PV rich system in greater depth with various factors governing the dynamic voltage signature of the system. The buses of the studied system are identified that have the least effect due to voltage disturbances. This study would help the planning of the power system through the identification of an individual or a group bus, where the controller or renewable energy generator could be integrated.

Further research is required in this domain. The power electronic load has been ignored in this work. Moreover, the interdependency of system dynamic signatures regarding transient voltage and frequency stability considering various compositions of renewable power generations and load would be studied in the future.

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