System Stability Impact of Large-scale and Distributed Solar Photovoltaic Generation: The Case of Ontario, Canada

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***Abstract*—This paper presents a comparative investigation of solar PV effect on system stability at different penetration levels. Three different scenarios with their relevant dynamic models are considered, namely, distributed units, and centralized farms with and without voltage regulation capabilities. Based on these models, the impact is examined through eigenvalue, voltage stability and transient stability analyses using real network data pertaining to Ontario and its neighboring systems. This impact is quantized in monetary terms based on the Long Run Marginal Cost of electricity production in Ontario. It is demonstrated that distributed solar PV generators are significantly more advantageous, from the stability point of view, than solar farms.**

***Index Terms*—Solar photovoltaic generation, stability studies, economic impact.**

I. Introduction

THE province of Ontario, Canada, is planning to phase out all coal generator units by 2014 [1]. This imposes a challenge to the province to ensure a reliable and adequate long-term supply of electricity. The Ontario Power Authority (OPA), as per the Green Energy Act [2], considers renewable energy sources as an important part of its long-range plan to meet this challenge. According to this plan, among different sources of renewable energy, solar photo-voltaic generators (SPVGs) are being given feed-in-tariffs (FITs) to encourage their deployment [3].

In a short duration of 7 years, from 2004 to 2010, the total global grid-connected solar PV capacity has increased at an average annual rate of 55%, to a total capacity of about 40 GW [4]. However, there are some technical concerns that need to be addressed to allow the grid to safely accommodate high penetration of solar PV units. Moreover, funding expensive renewables in lieu of cheap natural gas based generation is an important policy question that renewables face. Thus, tools and studies, as the one presented in this paper, that highlight the impact and contribution of the renewables for utility and system managers are certainly helpful in the context of these discussions.

Previous works pertaining to solar PV applications in power systems can be categorized into three major categories: modeling, technical impact, and financial planning. This paper concentrates on the first two aspects. Thus, from a modeling standpoint for power system studies, there are some manufacturer specific mathematical models for dynamic simulations developed by various vendors, with each having its own SPVG model. In order to utilize these proprietary models, special agreements with the manufacturer are typically required. Presently, no industry "standard" models for SPVG exist [5]. On the other hand, researchers have mostly focused on developing models for analysis of SPVG impact on power quality in distribution networks [6]–[8]. These models are very detailed, representing all switching characteristics of the SPVG. The detailed modeling required for fast switching transient studies is not necessary when only the slower cycle-to-cycle behavior of the SPVG system is of interest. Moreover, these types of switching models, if incorporated into conventional stability programs, would significantly complicate the required numerical calculations and hence are undesirable [9].

Some previous works have examined the effect of increased penetration of renewable energy sources, mostly wind energy, on power systems (e.g. [10], [11]). It has been argued that if a proper control strategy is used, there would be no considerable harm to system stability [12], [13]. The impact of solar PV in transmission systems has not been extensively studied; most of the technical literature concentrates on distribution system studies. Thus, the authors in [14] examine the electrical impact of solar PV penetration at the distribution level, and conclude that these plants may affect the voltage profile if they are installed in rural radial lines. In [15], a voltage control scheme is proposed to avoid voltage problems in distribution networks. The impact of small SPVG units on the operation of distribution systems is analysed in [16], [17], where it is indicated that considerable penetration of micro-generation may be accommodated safely without major modification to the system control. A correlation index is introduced in [18] to evaluate the impact of solar PV units on real power losses in distribution systems.

Based on the aforementioned shortcomings identified in the existing technical literature, two dynamic models for SPVG units, proposed in [19], are reviewed and applied in this paper. These models are based on previous WECC and CIGRE works, and are generic and non-proprietary, simple and readily implementable in any power system analysis package, and appropriate for transmission level stability studies. These dynamic models are used here to study the impact of penetration of solar PV on overall system stability. Thus, three types

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of stability studies are performed, i.e. eigenvalue analyses, loadability calculations, and time-domain simulations. Based on these studies, the effects of small distributed SPVG units and large centralized SPVG farms on transmission system operation are compared and analysed, with particular emphasis on the Ontario, Canada, grid. These studies are carried out considering different solar PV penetration levels to examine the interaction between traditional and renewable generation. Furthermore, the impact of SPVG on system stability is quantified in monetary terms considering the economics and associated system benefits accrued therefrom. A comprehensive operational data set of the Ontario power system is used for the studies presented in this paper, to study the impact of centralized and distributed SPVG in a real system. The main contributions of the paper can be summarized as follows:

- Comparisons of the stability impact of large centralized PV farms vs. several small-sized distributed PV installations are performed.
- Exact calculations of the impact are performed using the data set of a large real system and corresponding expansion plans, so that realistic scenarios can be considered.
- A complete and detailed evaluation is presented of Voltage stability, eigenvalue analysis, and time-domain simulations of a real system with various levels of distributed and centralized solar PV generation.
- Non-proprietary PV models based on a thorough literature survey are reviewed.

The rest of paper is organized as follows: The next section explores modeling of solar PV units, followed by a formulation of the various studies in Section III. The Ontario test system is briefly described in Section IV. Results and discussions are presented in Section V. Finally, Section VI highlights the main contributions and conclusions of the paper.

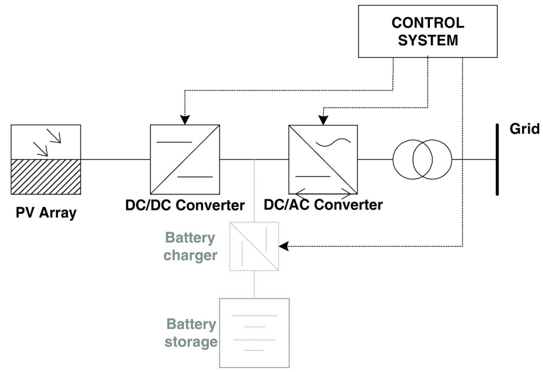

Fig. 1. Typical structure of a grid connected SPVG [20].

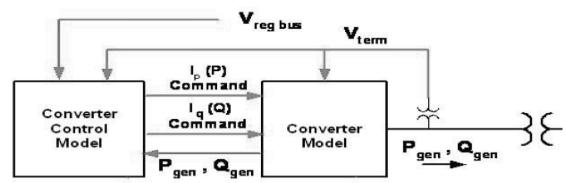

Fig. 2. Type 4 WTG general block diagram [24].

II. Dynamic Models of a Solar Photovoltaic Unit

The typical structure of a grid connected SPVG unit is shown in Fig.1. Its main subsystems are the photovoltaic array, the DC/DC and DC/AC converters, and the associated controls (converter and overall system) [20]. A storage system is in general absent in large grid-connected SPVG installations; however, there are reported instances in which considerable storage has been integrated into the SPVG unit [21], [22]. Maximum power point tracking (MPPT) in SPVGs is usually performed by a DC/DC converter at the output of the array, which regulates the voltage to the desired value. Since no moving parts are employed in this process, the response of the MPPT can be considered instantaneous for system stability studies. The remaining system components, i.e. dc bus, inverter and grid-connection devices, are similar to those found in some other distributed generators such as variable speed wind turbines, and therefore the dynamic modeling requirements are similar [20].

According to the North American Electric Reliability Corporation (NERC) [5], the SPVG model can be based on the grid-side model of certain types of wind turbine generators (WTG) that have a similar interfacing structure (Type 4 WTG), since SPVGs are typically connected to the grid through a converter. It is interesting to note that the SPVG models based on the Type 4 WTG are similar to those developed using a common sense approach [23]. Figure 2 shows a Type 4 WTG WECC generic model where all the power generated is processed through the power converter, which serves as a buffer between the generator and the grid, and controls the reactive power output and/or the voltage at the point of common coupling (PCC).

Two configurations are considered in this paper: centralized SPVG farms, and distributed SPVG units. It is a common practice to characterize the system buses using two out of the four electrical quantities, i.e. P, Q, V, and θ. Usually, active power injection with voltage magnitude or reactive power control are used to describe the buses for overall system studies of centralized SPVG; on the other hand, distributed SPVG units (e.g. roof-top panels) cannot regulate the voltage at the point of connection to the network. For centralized SPVG farms, which are in the range of tens of megawatts, some limited voltage control capability may be considered based on their reactive power control capabilities, which is the current trend across the world. Accordingly, distributed SPVG units are modeled as constant PQ negative loads, while centralized farms may

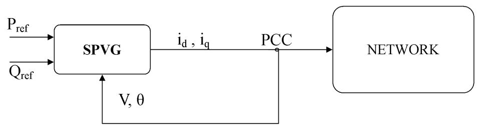

Fig. 3. SPVG Model 1 (PQ).

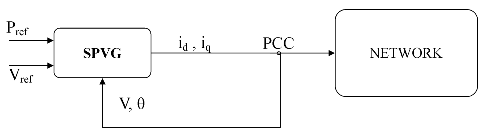

Fig. 4. SPVG Model 2 (PV).

be modeled as constant PV or PQ generators depending on the chosen control mode [10]. It should be emphasized that these are grid-side models as they are observed from the network, and thus no consideration is given here to distribution system level issues, which is reasonable for the stability studies discussed here. These functional models are referred here to as Model 1 and Model 2, and are shown in Fig.3 and Fig.4, respectively.

There are various models for inverter transfer functions; however, the following two are probably the most appropriate [23]: (a) first order functions with unity steady-state gain, and (b) closed-loop controller transfer functions. In [23], it is argued that both yield very similar results and hence the first is adopted here; furthermore, a first order model captures the main inverter characteristics relevant to transient stability (i.e. very fast transients are ignored), and is a typical approach used in these types of studies when modeling voltage source inverters (e.g. STATCOM inverter models used in [25]). Figures 5 and 6 show the detailed block-diagrams of Model 1 and Model 2, respectively. In these models, the current set points can be obtained based on the desired active and reactive powers and measurements of terminal voltage in the dq reference frame as follows:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} V_d & V_q \\ V_q & -V_d \end{bmatrix}^{-1} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{1}$$

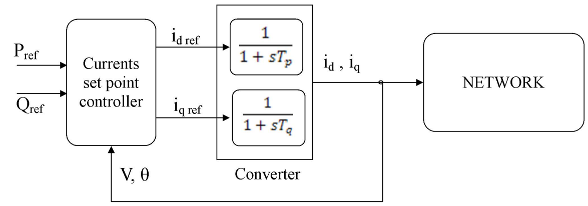

Fig. 5. SPVG Model 1 block diagram including the converter.

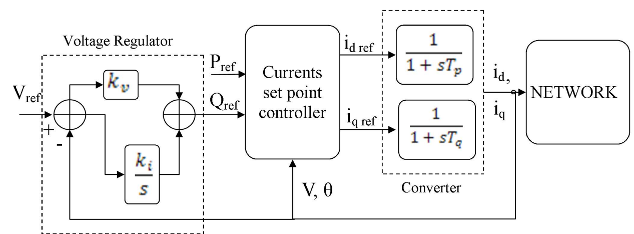

Fig. 6. SPVG Model 2 block diagram including the converter.

The power output for these models in the studies illustrated here, are assumed to be fixed or changing slowly during the day. The arguments to justify this assumption are presented in the Appendix.

III. System Impact Studies

The main focus of the paper is on stability studies of the system as impacted by SPVG penetration. However, the system stability margins and possible improvements from SPVG penetration may be translated into dollar-based figures to get a better insight on the advantages/disadvantages of this type of generation. This is carried out here through the use of Long Run Marginal cost and market prices [26].

A. Stability Studies

Three relevant types of studies are performed here, i.e. eigenvalue analysis, voltage stability and time-domain contingency analyses. Each of them is briefly explained in the following subsections, and are all based on a differential-algebraic equation (DAE) system model [27]:

$$\dot{x} = f(x; y; \lambda; \rho) \tag{2}$$

$$0 = g(x; y; \lambda; \rho) \tag{3}$$

where x is a vector of state variables pertaining to generators, loads and other system controllers; y is a vector of steady state algebraic variables that result from neglecting fast dynamics in some load phasor voltage magnitudes and angles; λ represents the uncontrollable parameters such as active and reactive power variations; and ρ is a set of controllable parameters such as tap or AVR set points. The nonlinear functions f and g stand for the differential and algebraic equations, respectively.

1) Eigenvalue Analysis: The system is linearized around an equilibrium point o, and the resulting system state matrix A can be defined as:

$$A = D_x f|_o - D_y f|_o \left(D_y g|_o\right)^{-1} D_x g|_o \tag{4}$$

where $D_x f|_o = \frac{\partial f}{\partial x}|_o$ is the partial derivative of f with respect to x computed at the equilibrium point o, and similarly for the other partial derivatives $D_y f|_o$, $D_y g|_o$ and $D_x g|_o$. The eigenvalues of matrix A are used to evaluate system stability [27].

2) Voltage Stability Analysis: If the system state matrix A has one zero eigenvalue with unique nonzero eigenvectors, or the eigen-system undergoes a discrete change that renders the system unstable due to the fact that some variables (usually reactive power generation) have reached their operating limits, then that operating point is associated with voltage instability [27]. In practice, this is studied by varying λ in (2) and (3), which typically represents load active and reactive power changes with respect to a base case as follows:

$$P_{Load} = \lambda P_{Load0} \tag{5}$$

$$Q_{Load} = \lambda Q_{Load0} \tag{6}$$

where, λ is used to study how much the system can be loaded, and thus, these are referred to as loadability studies, which are usually carried out using continuation power flows (CPFs). Typical system loadability margins obtained from CPF studies are shown in Fig.7. Since reactive power support plays a salient role in voltage stability, it is important to model the switching behavior of generator units from constant voltage to constant reactive power output properly when reactive power limits are reached. This applies to SPVG units as well.

3) Time-domain Contingency Analysis: The full behavior of the system can be captured through time-domain simulations. In this case, the nonlinear functions f and g in (2) and (3) are considered in the calculations, and after perturbing the system, variables such as voltages and frequency are monitored to determine whether operating limits are violated of not. Different contingencies are studied to determine the worst case scenarios in the system. For instance, the maximum time that a fault can be sustained while the system remains stable is called the critical clearing time (CCT), as depicted in Fig.8, and can be used as an index to evaluate relative system stability robustness [27].

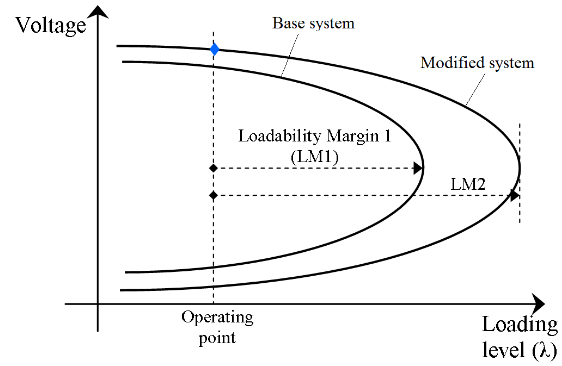

Fig. 7. The loadability margin under a specified system condition.

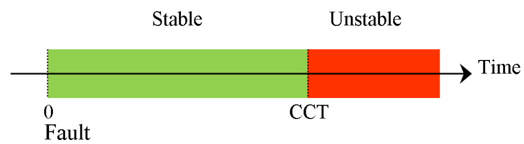

Fig. 8. The critical clearing time (CCT) for a specific contingency.

B. Economic Valuation

Two of the studies formulated in the previous subsections, i.e. loadability studies and time-domain simulations, address different time-frames of system dynamics. In other words, voltage stability and loadability analyses are usually based on slow system dynamics, associated with load evolution throughout the day, while time-domain simulations are used to study fast system transients associated with sudden contingencies. Based on these studies, as SPVG penetration level changes, different approaches can be used to quantify the economic impacts of this type of generation on the system.

An increase in the loadability margin means that there is an excess of capacity available for electricity transactions [27]; both generation and network constraints should be considered in these calculations. This indicator corresponds to the loading capability of the system. As shown in Fig.7, two different system conditions yield different values for the maximum loadability margin; for instance, these may correspond to the system without SPVG units (LM1), and with SPVG units (LM2). Hence, the extra capacity benefit available in the first case as compared to the second can be formulated as follows:

$$\text{LM benefit} = (\text{LM2} - \text{LM1})\ \text{LRMC} \tag{7}$$

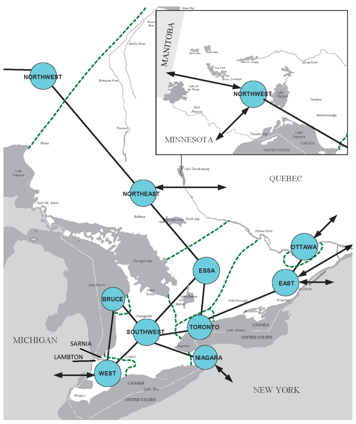

Fig. 9. Ontario's ten-zone model [28].

where LRMC stands for Long Run Marginal Cost [26], which refers to the cost of providing an additional unit of electricity under the assumption that this requires investment in capacity expansion. In other words, it reflects the cost of increasing the loading capability of the system (investments) and not merely the cost of electricity production.

IV. Case System Description: Ontario

An equivalent model for Ontario's transmission network is used for the studies reported in this paper. It includes ten zones for the province, as well as a few smaller equivalent subsystems to represent neighboring systems, i.e. New York, Quebec, Manitoba, Minnesota and Michigan (Fig.9). The IESO also uses a similar model to carry out reliability assessment of existing and committed resources and transmission facilities in the Ontario electricity market [28]. The inclusion of neighboring inter-connections is necessary, as there have been several incidents when the Ontario grid was impacted by these systems (e.g. the August 2003 blackout [29]). Another important feature of the Ontario system is the considerable distance between generator units in the north, mostly hydro, and the demand center in the south, mainly the Greater Toronto Area (GTA), which are connected through 500 kV lines. It is important to mention that roughly half of the demand in the province is supplied by nuclear units in the east and the west; hence, structurally, there is a tendency of oscillations between the west and the east of the system, which is avoided through power system stabilizers at selected generating units.

Actual system power flow data of Ontario is used in this study, which includes load, generation and voltage information at all buses. Line flows and losses are also available as a by-product of the power flow studies. The study system has 2975 buses and 4205 branches, including transformers. There are different voltage levels in the data set, ranging from 4 kV to 500 kV. The total demand for Ontario in the system model is around 25 GW, which corresponds to a peak summer demand. Based on the generator units ratings and types, their dynamic models are included [30]; accordingly, a sixth-order model is assumed for synchronous machines to capture their dynamic behavior and interactions [31]. Furthermore, a third-order IEEE Type AC4A excitation system is used [32], as they are common with steam units which are the prevalent generators in Ontario [30]. The loads are assumed to be constant impedance and fixed power loads for transient stability and voltage stability studies, respectively.

A large solar PV farm is assumed to be located in Sarnia, which is very close to the Lambton coal-fired power station (Fig.9); this is consistent with an 80 MW SPVG plant currently in operation near Sarnia. Considering the planned retirement of all Lambton units (4 x 490 MW) by 2014, as per the Integrated Power System Plan (IPSP) of Ontario [1], this power plant is chosen here to be phased out by solar PV generation, proportionally to the assumed penetration level. Thus, three scenarios are considered and compared: a centralized solar PV farm in Sarnia with voltage control capabilities, a similar centralized solar PV farm operating at unity power factor, and distributed solar PV units installed in the Toronto zone, replacing the Lambton units in all cases. The Toronto zone was chosen as the place for deployment of solar-rooftop units, given its population density and income levels. In this zone, 170 load points are considered, ranging from 280 kVA to 230 MVA. The aggregated effect of installing SPVGs at these points are simulated as a proportional reduction in their demand based on the assumed SPVG penetration level.

It is worth mentioning that under the current code of practice, unless the SPVG is a market participant, it has no obligations to provide reactive power support and is operated at unity power factor; however, this study explores the potential effect of large SPVG farms equipped with voltage regulators as compared to the effect of smaller, distributed D-SPVG units that cannot have any voltage regulation at the PCC.

V. Results and Discussions

All analytical studies were carried out using the DSA Tools [25], which is a commercially available software package that includes four components, i.e. PSAT, SSAT, VSAT, and TSAT; these are capable of performing power flow, small signal stability, voltage security and transient security analysis, respectively. The three scenarios described earlier are the centralized solar photovoltaic generator with voltage regulation (C-SPVG PV) , the C-SPVG with unity power factor (C-SPVG PQ), and distributed solar photovoltaic generators (D-SPVG). The model parameters used in Figs. 5 and 6, are as follows: $k_v = 0.0868$, $k_i = 50.9005$, and $T_p = T_q = 15$ ms.

A. Eigenvalue Analysis

The eigen-system was constructed and calculated for an SPVG penetration level up to around 2000 MW, which is equivalent to the total capacity of the Lambton generation station. The considered dynamic system has more than 1600 state variables, thus resulting in a similar number of eigenvalues.

The real parts of ten closest eigenvalues to the imaginary axis for different scenarios are shown in Figs. 10, 11, and 12. These show that each individual eigenvalue does not change considerably with the SPVG penetration level. Also,

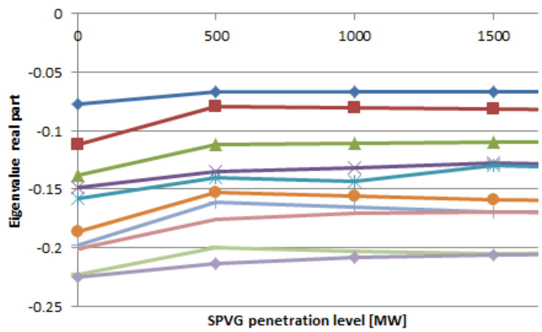

Fig. 10. Real parts of the eigenvalues as the D-SPVG penetration level increases.

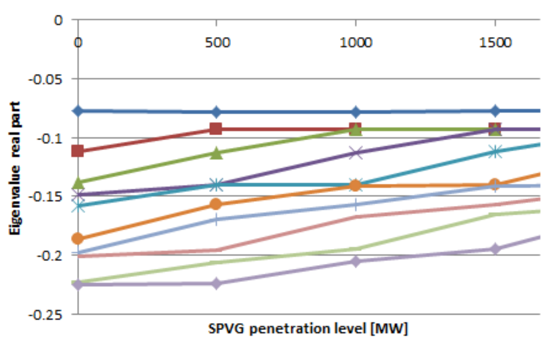

Fig. 11. Real parts of the eigenvalues as the penetration level increases for the C-SPVG PV case.

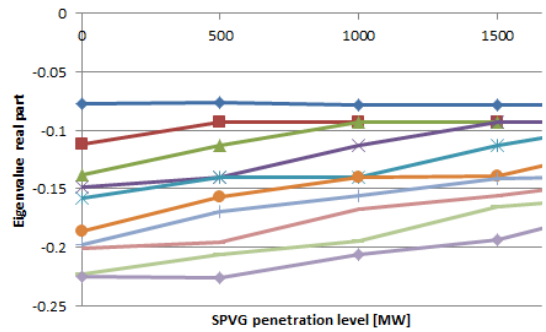

Fig. 12. Real parts of the eigenvalues as the penetration level increases for the C-SPVG PQ case.

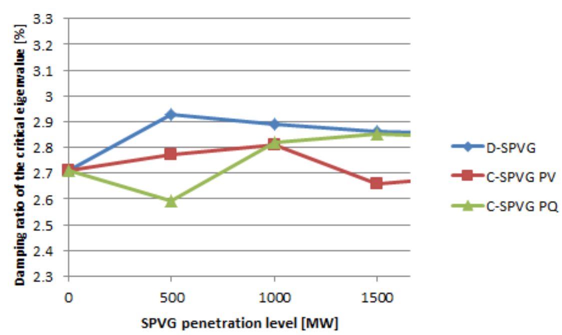

Fig. 13. Damping ratio of the closest eigenvalue to the imaginary axis as the penetration level increases for different scenarios.

the damping ratio of the closest eigenvalue to the imaginary axis for different scenarios is shown in Fig.13, and does not show any significant changes as the penetration level increases. This means that, at the studied operating points, SPVGs have no major effect on the overall eigen-system.

B. System Loadability Analysis

Loadability margins for different scenarios were calculated, and the results are depicted in Fig.14. Observe that the D-SPVG shows a considerable improvement in the system loadability while no significant change is seen in the C-SPVG PV and PQ cases as the penetration level increases. This is to be expected, since the C-SPVG PV is assumed to provide voltage regulation in the same area as the Lambton unit being phased out. The output power factor in this case is 0.99 which is very close to unity; thus, no considerable difference exists between C-SPVG PV and PQ. On the other hand, system loadability is significantly improved by D-SPVG installations, since this effectively corresponds to a load reduction in the main load centre of the Ontario grid, i.e. the Toronto zone.

Even though, the Toronto zone is assumed as the main sink of the province, Ontario has considerable power exchanges with its neighbours, especially New York. Thus, the change in the power export capability of Ontario to New York, is illustrated in Fig.15 as the SPVG penetration levels increase; for these studies, the sink was assumed to be NY, by increasing the load in this area while assuming that this is being supplied by generators in Ontario as the source. Based on these calculations, as explained in Section III-B, the long-run savings for loadability improvements as SPVG penetration level increases can be calculated as depicted in Fig.16. The LRMC value used for this calculations was 108.4 \$/MWh, as per [33]. Notice the savings achieved as the D-SPVG penetration level increases, while these are negligible in the C-SPVG PV and PQ cases. The corresponding annual savings can be calculated using the associated annual load duration curve of the system; thus, this curve indicates the number of hours per year that the load is greater than a given level. Accordingly, in Ontario, the load is greater than 23 GW for 146 hours per year [34]; this load level was used because the peak load in Ontario is in the order of 25+ GW, while the SPVG capacity considered here

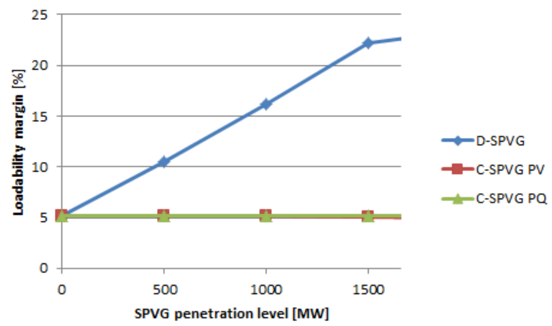

Fig. 14. Loadability margin of the system as the SPVG penetration level increases.

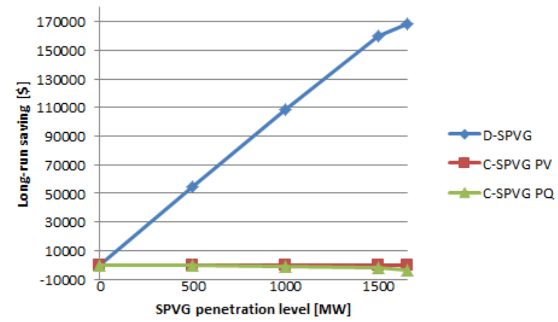

Fig. 16. Long-run savings from loadability improvement as SPVG penetration level increases.

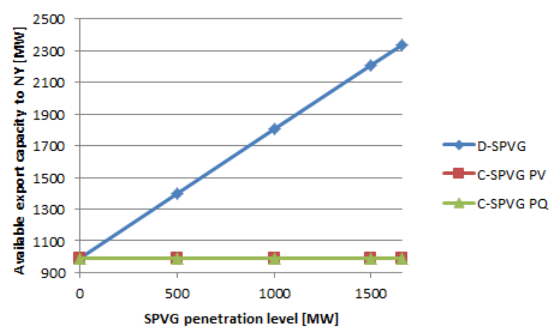

Fig. 15. The export capability from Ontario to New York as SPVG penetration level increases.

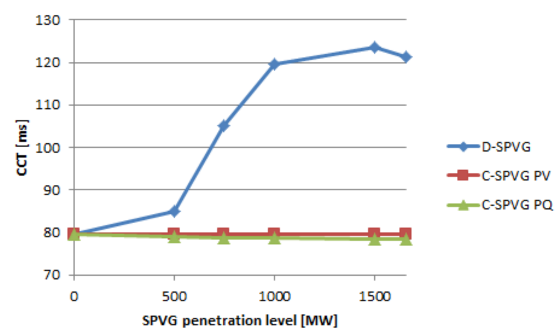

Fig. 17. Critical clearing times as the SPVG penetration level increases.

is approximately 2 GW. In Ontario, the wholesale electricity price and the payments are calculated on an hourly basis. Thus, approximate annual savings of 146 hrs $\times$ 168,778.8 \$/hr $\approx$ \$24.6 million may be expected for 2 GW of D-SPVG, based on the figures depicted in Fig.16.

C. Time-domain Simulations

A sustained 3-phase fault is considered in the middle of one of the 500 kV lines connecting the Bruce to the Southwest (Milton) zones near the Toronto zone. This line is chosen because it supplies a significant portion of the demand in the Toronto zone. Thus, the SPVG penetration levels may have a considerable effect on the system response to this critical contingency. The simulation length is 20 s, and the fault occurs at $t = 10$ s.

The CCTs for different penetration levels obtained in this case are depicted in Fig.17. Observe that the C-SPVG PV and PQ do not have any considerable impact on the system response, as the CCT remains almost unchanged at around 80 ms. On the other hand, there is a significant change in CCT values as the penetration level for D-SPVG increases. These results are consistent with the aforementioned loadability studies in terms of system impact, demonstrating that D-SPVG improves system stability significantly as compared to C-SPVG.

The CCT is not usually used as a stand-alone index to evaluate transient stability of power systems, but it can be used for comparative analyses of system stability under different system conditions. Thus, Fig.18 shows the Bruce generator frequency before, during, and after the fault occurrence for the three different scenarios considered, i.e. D-SPVG, C-SPVG PQ, and C-SPVG PV with the SPVG penetration level at its maximum. The fault duration is 4.7 cycles for all the cases, which is the CCT for the C-SPVG PQ case. Note that C-SPVG PQ and PV curves are almost indistinguishable, and, as expected, the D-SPVG case shows the least frequency variations. There is a steady state error in the generator frequency because no AGC (Automatic Generation Control) has been considered in the system model. Also, the voltage magnitude at the receiving end of Bruce-Milton line is shown in Fig.19. Observe that the voltage profile is better in the case of D-SPVG because of the reduced stress on the transmission system.

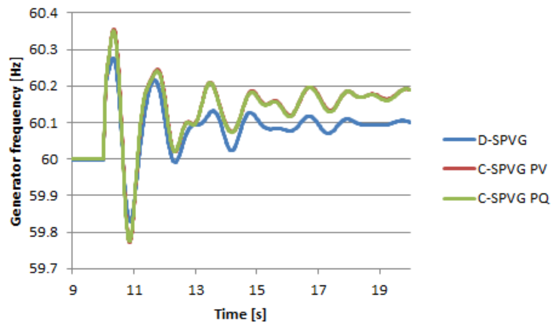

Fig. 18. Bruce generator frequency during the fault simulations.

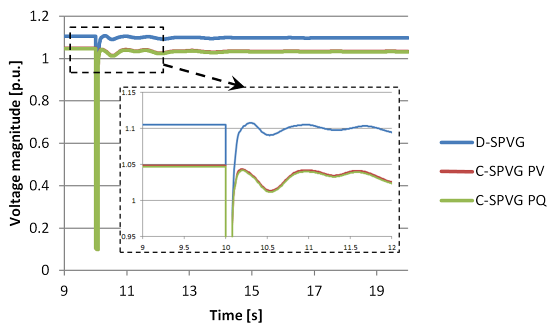

Fig. 19. Voltage magnitude at the receiving end of the Bruce-Milton line during the fault simulations.

It is important to mention that the studies presented here were performed at the transmission system level and do not reflect possible local issues associated with distribution systems. Moreover, even though these studies were performed for the Ontario grid, similar results would be expected for other large systems, where significant advantages in terms of stability may be expected from D-SPVG at large load centers.

VI. Conclusion

In this paper, the impact of SPVG penetration level on the stability of Ontario power system was assessed. Ontario's system data was used in these studies to obtain a better understanding of the interactions between the SPVG and a real system. Three scenarios with their relevant grid-side dynamic models for the SPVG were considered; these non-proprietary models can be used to represent centralized farms, with and without voltage control, and distributed rooftop installations.

The dynamic behaviour of the system including SPVG installations was examined for different penetration levels, by means of small-signal stability, voltage stability and time-domain contingency analyses. Eigenvalue analysis showed that SPVGs have no major effect on the overall small-signal stability of the system. Voltage stability and transient stability studies, on the other hand, demonstrated that the D-SPVG can considerably improve system stability with respect to the C-SPVG.

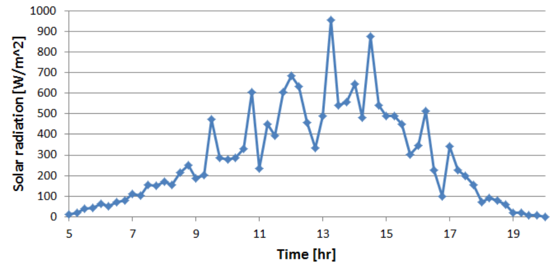

Fig. A.1. Solar radiation in mid-June in Waterloo, Southwestern Ontario.

Appendix
Variation in the Solar Irradiation Levels

Changes in the active power generation from a PV installation are inevitable because of the variation in the solar irradiation, which in turn, depends on weather conditions. However, the total solar generation at its maximum penetration level makes around 6% of the system power generation in the presented study. Therefore, the variations would not be expected to cause a drastic change in the results, given that the study uses a data set pertaining to a summer day and hence clouding effects should be minimum. Moreover, the land area required for the panels distribution and installation is considerably large, resulting in a natural averaging effect which filters possible sharp changes, thus minimizing temporary clouding effects.

Since, the data set belongs to the peak load in the mid-June, Fig.A.1 shows irradiation levels for that day in Waterloo, which is located in Southwestern Ontario; note that this figure shows the raw data of the irradiation levels for one physical point in 15-minute intervals without any averaging effect. Furthermore, the output of an actual roof-top PV installation in this location (at one of the University of Waterloo buildings) is shown in Fig.A.2; the initial jump is due to shading from a nearby building in the morning. Observe that the output is quite smooth when the PV panels are receiving enough irradiation. To complement this observation, the actual output power of a 10-MW unit in operation in Sarnia, Southwestern Ontario (the assumed location for the C-SPVG) is shown in Fig.A.3. This measurement pertains to June 15, 2012. These figures provide further argument to justify the use of fixed or slow-changing C-SPVG and aggregated D-SPVG powers to study the presented system.

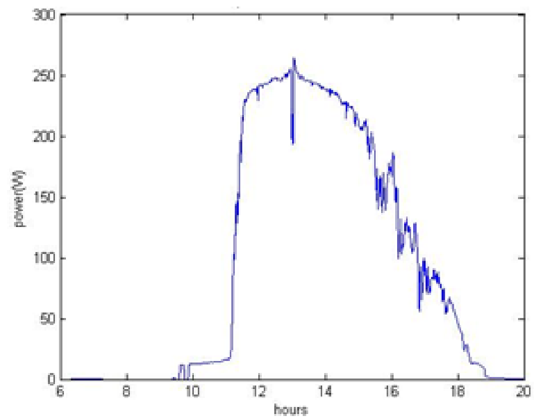

Fig. A.2. The power output of a roof-top PV installation in Waterloo, Southwestern Ontario.

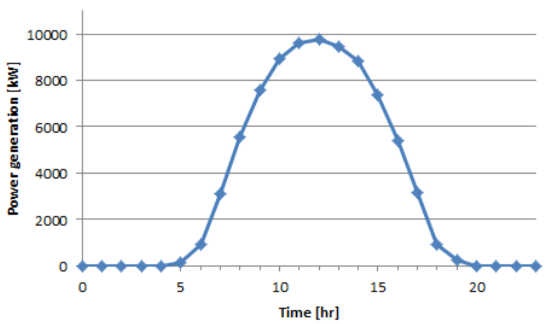

Fig. A.3. The measured output power of a 10-MW C-SPVG unit in Sarnia, Southwestern Ontario.

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