Virtual Inertia Based PV Systems

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It is well known that a plethora of issues can arise when a reliance on non-solar energy is present. These issues include air/water pollution, a depletion of natural resources, environmental damage, and endangerment to animal/human health [2]. Thus, the rise and improvement in solar energy resources has created an effective solution to these issues. Photovoltaic (PV) sources convert sunlight into energy, therefore creating a clean means of energy. Solar renewable energy resources stereotypically provide low inertia, which decrease the control time of the system, therefore decreasing the overall system efficiency [5]. Additionally, low inertia can make a system susceptible to noise and oscillation. To combat this issue, virtual inertia-based PV system implementations are being studied and simulated. Furthermore, testing of how the addition of inertia can affect a systems overall efficiency and stability is being conducted, as the addition of inertia stabilizes the grid frequency [3].

The increased implementation of solar generation systems has led to a decrease in their overall inertia coefficient, as the kinetic energy that the spinning generators created are replaced by non-spinning ones. Typically, solar generation optimizes a voltage source converter (VSC), which adds no kinetic energy - and therefore no inertia - to the system [4]. As stated previously, a low inertia point decreases the stability and efficiency of the system, leading to the obvious hypothesizing of ways to create inertia in these systems. Virtual inertia-based PV systems for smart grid applications have become an increasingly researched topic, as it is the most practical and cost-efficient solution to the issue [4]. Several different implementation approaches of virtual inertia have been attempted, simulated, and published, and will be references in the following paragraphs.

The first implementation of an inertia-based PV system that will be analyzed is the DC-Link approach. Traditionally, the inertia of a system shows the rate of change of the frequency at a supply/demand imbalance, or the active power changes (ΔP). Furthermore, the active power changes in the system can be modeled by:

$$\Delta P = \frac{2H_{VSC}}{f_o}\frac{df}{dt} \qquad [5]$$

where H_{VSC} is the virtual inertia coefficient (or the stored kinetic energy, W_E, divided by the rated power of the PV generator, S_{VSC}), f is the measured frequency of the model, and f_o is the nominal frequency of the system [2]. Note that virtual inertia can be achieved through the addition of any short-term energy bank [3]. With this in mind, the DC-Link voltage simulation can be analyzed. A block diagram for a two-stage PV system that optimizes the DC-Link voltage for inertia emulation is shown in Figure 1.

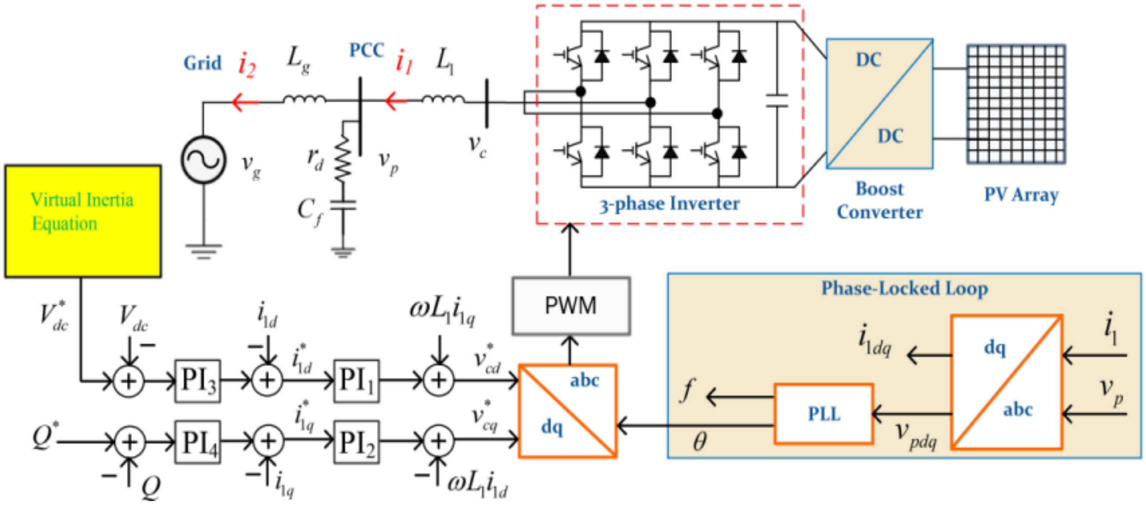

Figure 1: Two-Stage PV System Controls Block Diagram [4]

The Virtual Inertia Equation, also shown in the figure, is characterized by the DC-link reference point. Though several extra parameters are used in initial calculations, source [4] shows the simplification of setting several to 1 because of their lack of impact. The simplified equation is shown as:

$$Vdc = \frac{2H_{VSC}S_{VSC}}{f_o * C_{dc}V_{dco}}(f - f_0) + V_{dc0} \qquad [4]$$

where C_{dc} is the DC-Link capacitance and V_{dc0} is the nominal DC-Link voltage. The result of this equation is sent through proportional integral (PI) controllers and a pulse width modulator, among other circuitry, which is then fed into the inverter. The effects of the addition of the DC-Link capacitor were analyzed through MATLAB/Simulink. The stability of the system was found to have improved after an eigen locus plot were plotted and none of the poles were found to be in the right-half plane. This is shown in Figure 2. Thus, it can be concluded that more inertia emulation was achieved through the state of the capacitor (charged vs. discharged) without compromising the stability of the system [4].

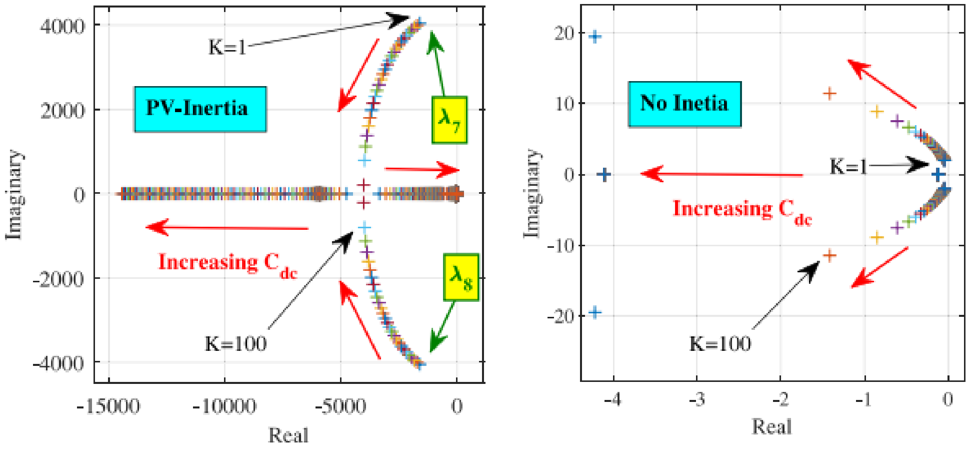

Figure 2 – DC side capacitor effect on eigenvalues with and without virtual inertia loops [4]

Another method to aid in the addition of inertia that has been tested surrounds using the Virtual Synchronous Generator (VSG) as an inverter control method. The implementation of this VSG as a controller is shown in Figure 3, where the PV reading is sent through a DC filter bus to the inverter, while the load and PV reading are both circled into the inverter after the feedback is used in the controlling of the device through the VSG. Therefore, both the input and the output feedback lines are taken into account by the controller, and the idea here is that this VSG control can create the virtual inertia needed to stabilize the system. The block diagram of this idea is shown below.

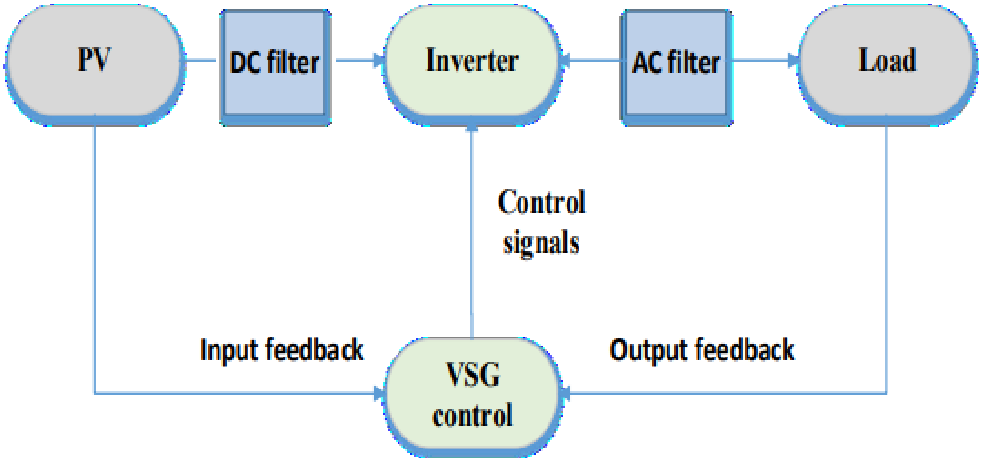

Figure 3 – Showing the VSG used as a controller [1]

As stated previously, most PV systems do not include a rotating mass to provide inertia, so the addition of a VSG can emulate this inertia and therefore better the system [6]. Using the VSG as an inverter can also help to control the oscillation frequency with added noise and decrease active power oscillation [1]. It is clear from the block diagram in Figure 3 that the VSG is controlling the inverter based off the PV system and the load. This allows for proper stability, as it is the control is directly based off those inputs. Moreover, the governing equation for the inertia response (P_{in} - P_{out}) that uses this VSG control method is:

$$P_{IN} - P_{OUT} = \mathrm{J} * w_m \left(\frac{dw_m}{dt}\right) - D(w_m - w_g) \qquad [1]$$

where P_{in} and P_{out} are the input and output powers to the inverter, J is the moment of inertia, D is the damping factor, w_m is the virtual angular frequency, and w_g is the grid angular frequency [1]. Based off the previous discussion, it is a fair assumption that the moment of inertia is to have the greatest increase possible while maintaining the least amount of change in the other variables. This idea is more clearly illustrated in the block diagram below, where the VSG control is shown in a different light.

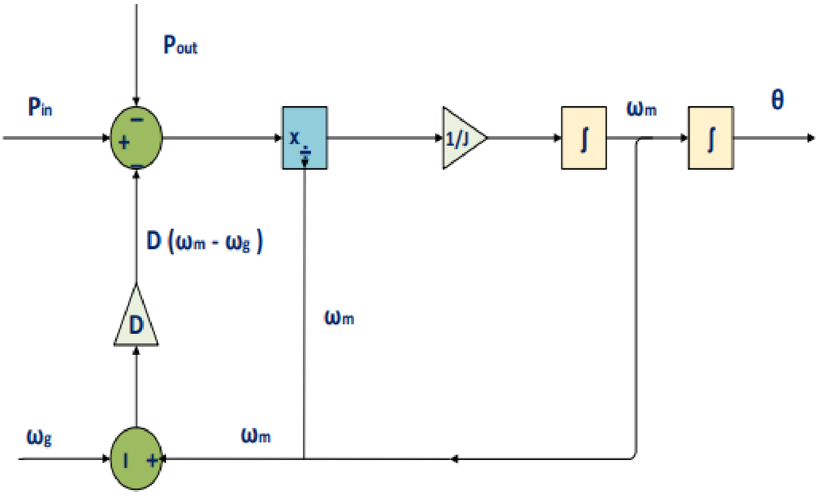

Figure 4 – Controls diagram of the operation of VSG [1]

Note that the electrical angle frequency, ϴ, is used in conjunction with pulse width modulation to create the control signals for the inverter. The results of this implementation were fairly positive – the system behaved as expected. Moreover, the steady-state error is practically obsolete, the settling time is decreased, and the overshoot is slightly smaller [1]. These positive improvements show that the control of the VSG is benefitting the system and could be the basis for other future improvements and work on the system. Overall, there were several positive effects after the implementation of the VSG, and the exploration of its full potential is continuing to be studied. As with many PV related studies, the field is growing rapidly because of the quickly multiplied use of solar energy, as it is a means of clean energy. With this growth in demand comes the issue of stability, as the grid is not receiving the inertia that it is used to [5]. Though devices such as wind turbines can aid in the development of this inertia, the overall input into the grid is too small and is only going to become more of an issue as time goes on and PV systems become more and more common. Moreover, the VSG provides a way to improve the stability of the system in several different ways. Some of these improvements can be seen in Figure 5 below. Note that the graph is depicting the load active power over time to display these characteristics. Other results from this technique include damping of the oscillation at steady state and enhancement in stability shown through the DC voltage response.

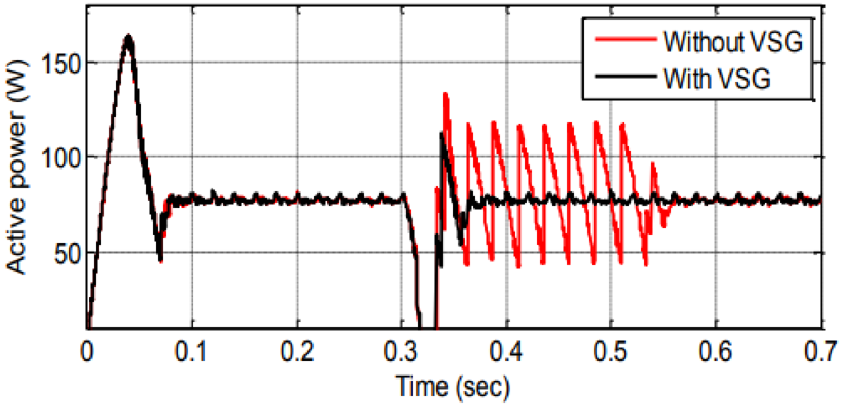

Figure 5– Load active power response over time [1]

The next test performed in this application revolved around finding the limits of the systems parameters and picking values that optimally run the system. Parameters including the DC-Link inductor, DC-Link Capacitor, moment of inertia, damping factor, AC-side inductor, and AC-side capacitor were studied. The effect that changing these parameters had with the PV source and on the frequency response were both studied. For instance, increasing the DC-Link capacitor from 4000uF to 7000uF resulted in a small increase in overshoot and a decrease in the settling time, while a decrease to 800uF resulted in an increase in overshoot and an increase in settling time [1]. Additionally, increasing the moment of inertia by a factor of 10 (from 56 kg*m^2 to 560 kg*m^2) resulted in an increase in both overshoot and settling time, while decreasing by a factor of 10 resulted in a small decrease in overshoot and a continued increase in settling time

[1]. The original parameters for almost all of the values used in the system that were changeable were tested with both increased and decreased numbers, and the results were scattered. Some changes, such as decreasing the DC-Link capacitor, would result in positive changes [1]. However, the opposite would result in result in system instability. The full results of the effects on the frequency response of the system are shown in Table 1 below

Parameter	Change	Effect on Performance
DC-Link inductor	Value decreased	Decrease in overall system overshoot
DC-Link capacitor	Value increased	Decrease in overall system settling time
Moment of inertia	Value decreased	Small Decrease in overall system overshoot
AC-side inductor	Value decreased	High Decrease in overall system overshoot
AC-side capacitor	Value decreased	Decrease in overall system overshoot

Table 1 – Frequency response characteristics with changing parameters [1]

Based on these results, there are a few things that immediately come to mind in regards to future work and studying relating to virtual inertia-based PV systems. With emphasis on the DC-Link capacitor, different sized capacitors, different voltage converters, and different inductor values can all be tested an endless amount to create an optimal system. When it comes to the VSG controller, analyzing the system further when the AC side inductor is decreased from 4 mH's to 1 mH is worth studying, as it provided a decrease in settling time that was seen in both the PV source and the frequency response. This seems to be the most promising test that can be conducted, as simulations showed that there would be immediate improvements to the overshoot and the settling time. As a whole, the topic of virtual inertia-based PV systems is a fairly new idea, that is progressing overtime. The studies referenced in the research mentioned were all conduced within the past 4 years, further emphasizing the progressiveness of the idea. A fair prediction that the ideas for future work/improvements that were listed previously will be tested in the coming years can be made. Overall, the topic is ever-growing, good for the environment, and better for humanity as a whole.

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