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OPTIMAL CONTROL OF HYBRID PHOTOVOLTAIC/BATTERY ENERGY STORAGE SYSTEM FOR MITIGATING VOLTAGE SAG

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ABSTRACT

This paper presents development of an optimal control strategy for a hybrid photovoltaic/battery energy storage (PV/BES) system. The fluctuations at the DC bus voltage due to voltage sag were mitigated by using charge/discharge capability of the BES through the DC/DC buck/boost converter. Furthermore, an optimization of system control parameters responsible for DC bus voltage regulation within the grid side voltage-sourced converter and DC/DC buck/boost converter were introduced by using simplex optimization method. The control system performances were evaluated for different simulation case studies such as the cases with and without BES as well as the system with optimized control parameters.

Key Words: Photovoltaic, Battery energy storage, DC bus voltage regulation, PI controller, Parameter optimization

INTRODUCTION

In Malaysia, the investment in photovoltaic (PV) based distributed generation (DG) system has shown an exponential increase in recent years since the introduction of feed-in-tariff program with applications soared up to 87.7% by end of last year (Yee 2011). Consequently, with increased development and deployment of storage technologies, particularly the battery energy storage (BES) system, the operation of grid-connected PV system can be enhanced by utilizing the battery energy to properly manage the output of PV system so as to improve efficiency (Daud et al. 2012). A voltage-sourced converter (VSC) is practically used to interface the hybrid PV/BES system, where

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control and transfer of power to utility grid is performed according to required interconnection standards (IEEE 2004).

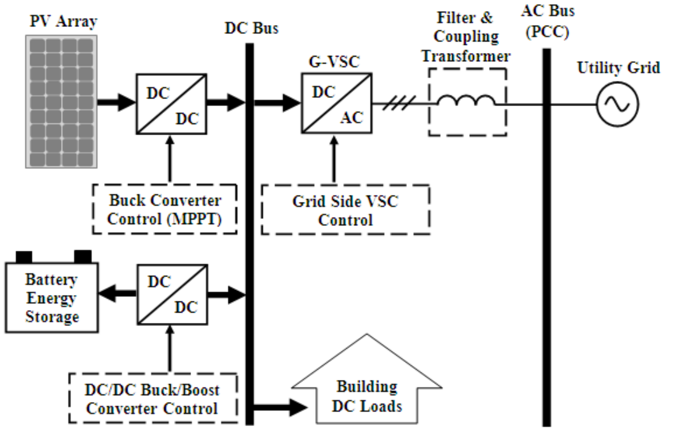
When a system is subjected to a disturbance from a utility grid, the control system is responsible in ensuring that the DG is always connected to the grid so as to provide a continuous supply of power to the loads in the vicinity including critical loads. Amongst the power quality problems which can cause instability of the connected DG, voltage sag is the most common disturbance which affects the performance of a VSC (Hajizadeh and Golkar 2010). Voltage sag is defined as a drop in RMS voltage with duration between 0.5 cycles and one minute where the majority of sags are caused by short-circuit faults (IEEE 1995). With large DG penetration, such as multiple connections of PV system to the network, the disconnection may cause serious problems such as power generation deficits, instability and disconnection of critical loads. Therefore, it is of significant importance to consider the interaction between a PV system and the utility grid during voltage sag and this needs to be taken into account in designing a proper control system. For example, the capability of system controllers in regulating the DC bus voltage of a PV system should be properly investigated because a constant DC bus voltage seen by the grid side VSC (G-VSC) results in efficient power conversion and improves stability while protecting the DC bus capacitor and the VSC valves against overvoltage stress.

In this study, an optimal control scheme for a hybrid PV/BES system is developed. The method employed parameter optimization for VSC and BES buck/boost converter controllers with the objective to minimize the input DC bus voltage errors processed by the proportional and integral (PI) compensators. The effectiveness of the proposed parameter optimization method is evaluated by comparing with the conventional hand-tuning method for the case of DC bus voltage regulation. In addition, the effect of using BES as an additional source for compensation is also presented.

PV/BES HYBRID SYSTEM

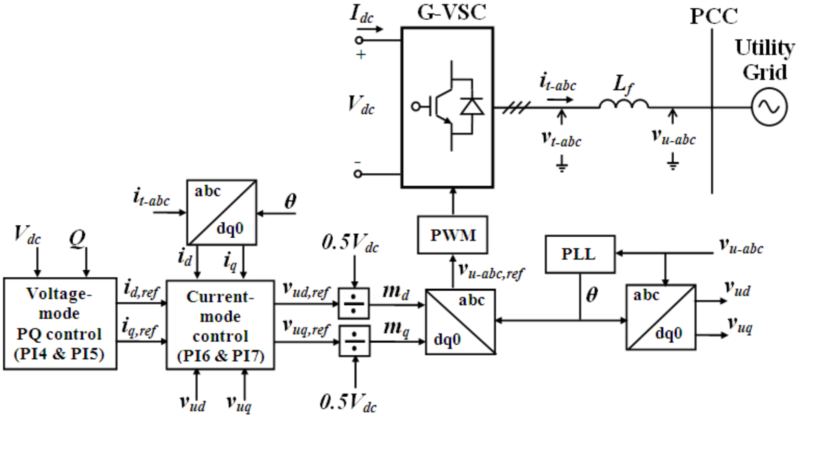
Figure 1 shows the system's layout for the considered PV/BES hybrid system consisting a PV array interfaced to the DC bus through a buck DC/DC converter with MPPT (Hussein et al. 1995). BES is connected to the DC bus via a bi-directional DC/DC converter for control of BES charge/discharge operation while the G-VSC is used for grid interfacing. An equivalent inductor represents the total inductances of system filter and coupling transformer which ensures the injected harmonics follow the required standard (IEEE 2004).

Figure-1. Schematic of the proposed PV/BES system



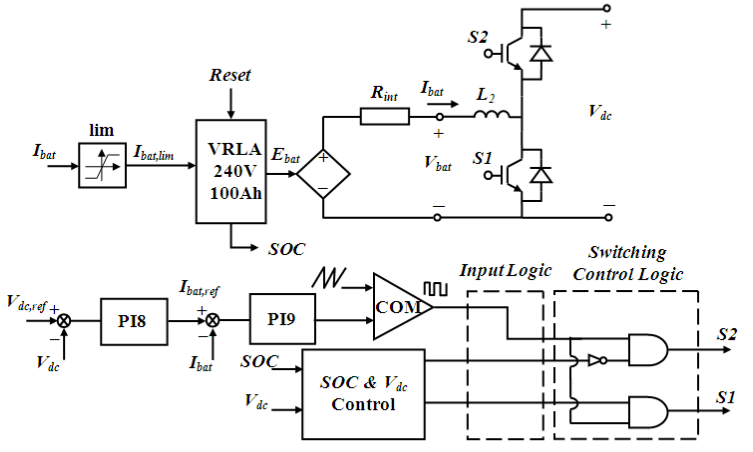
Control of G-VSC employs the closed-loop decoupled current control method which is based on the *d-q* rotating reference frame as shown in Figure 2 (Yazdani et al. 2011). The controller ensures a smooth power flow to the utility grid while keeping the injected power at unity power factor. An efficient VSC operation is resulted from the regulation of DC bus voltage and compensation of reactive power at the outer PI control loops compensated by PI4 and PI5, respectively.

Figure-2. Control of G-VSC



For the BES buck/boost converter (Figure 3), a control algorithm is developed to ensure safe and optimal operation of BES while providing additional support for DC bus voltage regulation (Daud et al. 2012). The control for charge/discharge to compensate the DC bus voltage deviations is achieved through PI8. The controller utilizes logic circuits for the decision of operation modes of BES including charge/discharge or stopping mode. Switch S1 is triggered and S2 becomes zero during the discharge (boost) mode and vice versa during charging (buck) allowing BES to absorb power from the DC bus. Both switches become zero when no regulation signal is transferred.

Figure-3. Control of BES buck/boost converter



CONTROL PARAMETER OPTIMIZATION

To improve the DC bus voltage regulation, the optimization approach uses the simplex algorithm developed by Nelder and Mead (1965). The objective function (OF) is designed based on error minimization problem using weighted integral squared error (WISE) as the performance index and described as follows:

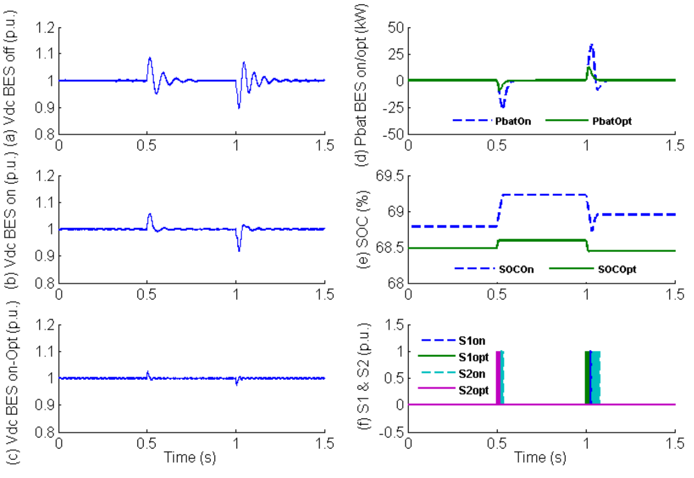
$$OF(n) = \int_{T_0}^{T_1} W_1 (V_{dc} - V_{dc,ref})^2 \, dt + \int_{T_1}^{T_F} W_2 (V_{dc} - V_{dc,ref})^2 \, dt \quad , \qquad (1)$$

where $n = (K_{pd4}, T_{id4}, K_{pb8}, T_{ib8})$ is the set of control system parameters for PI4 and PI8, respectively. T_0 is the time at which the reference is changed within the entire length of the simulation time (T_F), and T_1 is a suitably selected intermediate point that permits the assignment of different weighting factors (W_1 and W_2) to the initial and latter portions of the response. The optimal parameters obtained are used for performance comparison with the results based on conventional hand-tuning method studied for DC bus voltage regulation.

RESULT AND DISCUSSION

The test system configuration shown in Figure 1 was simulated in the PSCAD/EMTDC program. Here, the PV array is scaled to produce a 200kWp power at STC, while 100Ah BES is selected to allow maximum discharge current of 300A during the most severe case considered. Different simulation case studies are carried out to evaluate the effectiveness of using BES and the proposed control parameters optimization technique for improvement of DC bus voltage regulation. Figure 4 shows a comparison of DC bus voltage profiles with the corresponding BES charge/discharge operations when the system is subjected to utility grid fault at the PCC at magnitude 0.5 p.u.

Figure-4. Effects of BES compensation and control parameters optimization on DC bus voltage regulation

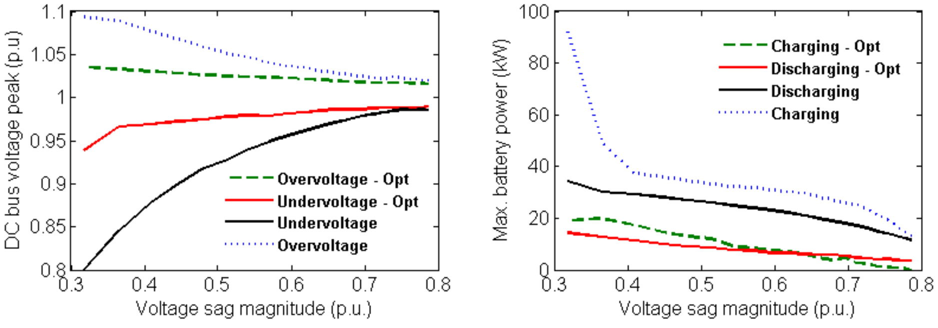


From Figure 4(a)-(c), the overall improvement in voltage regulation is pronounced for the three different cases studied. Without BES compensation (Figure 4(a)), the DC bus voltage fluctuates with overvoltage/undervoltage spikes within 10% and the transient settling time in the order of hundreds of milliseconds. However, with BES connected, the bus voltage transient is more stable with deviations to the reference value approximately between 5% and 7%. Moreover, with optimized control parameters (Figure 4(c)), the bus voltage exhibited high stability with only marginal overshoot/undershoot as well as improved transient performance. The deviation of the voltage overshoot/undershoot to the DC bus reference value are measured at approximately 2% and 3%, respectively.

It is evident that from the comparison of results shown in Figure 4(b) and (c), the optimized control parameters provide an optimal system controller with DC bus voltage relatively constant seen by the G-VSC. Moreover, the use of BES energy can be minimized with improved control system performance as can be seen from Figure 4(d)-(f).

To statistically analyze the effects of varying the voltage sag magnitude at the PCC to the DC bus voltage ripples as well as BES sizing requirements, the results in Figure 4 are extended for the case of voltage sag magnitude ranging between 20% and 70%. Figure 5 shows the comparison of system controller performance for the conventional hand-tuning method with the optimized one. From Figure 5(a), with optimized system control parameters, the DC bus voltage ripples can be kept below 5%. Furthermore, the requirement for BES size for compensation can also be minimized where only a maximum of 20 kW power required for the most severe case considered (Figure 5(b)). This can be attributed to optimal system performance of the PV/BES hybrid system resulting from optimization of control system parameters for the VSC and BES buck/boost converter.

Figure-5. Effects of voltage sag magnitude on DC bus voltage overvoltage/undervoltage peaks and BES energy requirements



(a) (B)

CONCLUSION

The paper has presented the improvement of DC bus voltage regulation strategy for a hybrid PV/BES system against voltage sag. A stable DC bus voltage seen by the grid side VSC contributed to an efficient performance and improved operation of the PV/BES system. This can be attributed to the role of BES in improving the DC bus voltage by charging/discharging processes through the buck/boost converter. Optimization of the control parameters further improved the overall performance while contributing to minimum size requirements of the BES used for this application.

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