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Research on the efficacy of integrated fuel cell and distribution static synchronous compensator in improving power quality on distribution networks with photovoltaic systems

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Abstract. The increased penetration of intermittent energy sources has the potential to cause voltage fluctuation and flicker. Static synchronous compensator has been proven to be one of the solutions to solve this issue. Integrating an energy storage system with a static synchronous compensator can increase its performance for real power compensation. While batteries are the preferred solution for photovoltaic power fluctuation mitigation, fuel cells have several advantages over batteries. Based on literature review, integrating a static synchronous compensator with fuel cells can compensate for the fuel cell's slow response time for transient stability improvement. Hence, this paper presents a model and control scheme of an integrated distribution static synchronous compensator with fuel cell on a distribution network with a grid-connected photovoltaic system. A proportional-integral controller is developed to manipulate the real and reactive power flow for power and voltage regulation. The distribution network is modelled in MATLAB Simulink and the performance of the proposed system for voltage fluctuation and flicker mitigation is evaluated. Results show that the proposed system can reduce flicker levels by more than 80% as well as regulate the voltage on the network at 1.0 p.u.

1. Introduction

Renewable energy sources have seen rapid growth in recent years. This is due to its potential to reduce Greenhouse Gas (GHG) emissions by cutting down on the reliance of fossil fuels in electricity generation. However, one of the major problems of renewable energy sources such as solar or wind energy is that high levels of renewable energy penetration can cause negative impacts to the power quality of a grid network [1]. In Malaysia, there is a high frequency of passing clouds, thus contributing to the high intermittency of solar irradiance. This may cause voltage flicker levels to exceed the statutory limits when there is high photovoltaic (PV) penetration into the grid [2]. High levels of voltage flicker may cause flickering in computer screens and cause people who use computers to experience various health issues such as headaches, epilepsy, and seizures.

One of the solutions that can improve power quality in the network is the use of a Static Synchronous Compensator (STATCOM) for the transmission network or Distribution Static Synchronous Compensator (DSTATCOM) for the distribution network. STATCOM has been shown in studies to be



able to improve power quality issues caused by multimachine power systems as well as renewable energy systems on the grid [3]. However, STATCOM cannot perform real power compensation due to the lack of an energy storage system. Hence, supporting the DC side of STATCOM with batteries or fuel cells can improve the functionality of STATCOM [4].

Currently, batteries are the preferred solution for PV power output fluctuation mitigation [5]. However, fuel cells have several advantages over batteries as it does not suffer from self-discharge and can be fully discharged without suffering from a loss in capacity [6].

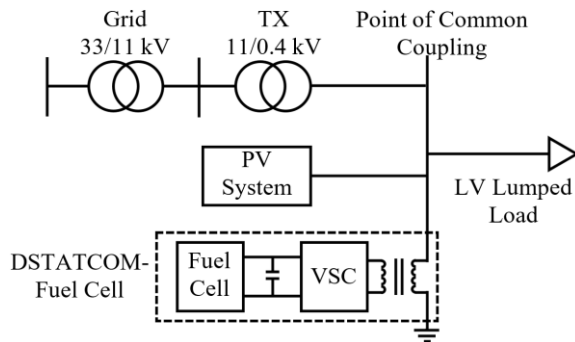
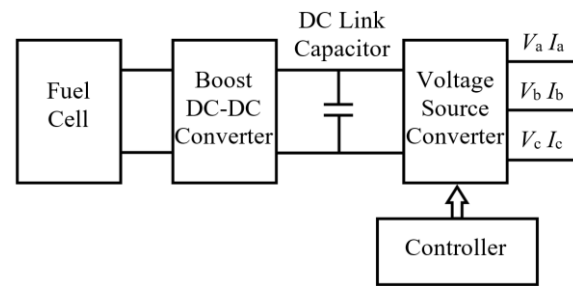
Numerous research efforts have studied the use of hydrogen energy storage systems which consists of fuel cells, an electrolyzer, and a hydrogen tank for PV power output fluctuation mitigation. The viability of using a hydrogen energy storage system for reliability improvement of power generation from a PV plant to the grid is investigated in [7]. A method of using a hydrogen energy storage system with an exponential smoothing algorithm to suppress short-term PV power fluctuations which does not require meteorological forecasting is presented in Tesfahunegn et al. [8]. Li et al. have presented a self-tuning fuzzy-Proportional Integral (PI) controller for a fuel cell system to address power quality issues from frequency deviations caused by intermittent energy sources [9].

One of the drawbacks of fuel cells is its slow response time. This causes fuel cells to have inferior performance to batteries for power fluctuation mitigation. However, Stella et al. have reported that integrating fuel cells with STATCOM can improve the slow response time of fuel cells. The transient stability enhancement capabilities of STATCOM/Fuel-cell was evaluated and was found to outperform STATCOM/BESS in overshoot and settling time improvement [10]. In Sundarabalan & Selvi, a control scheme for DSTATCOM/Fuel-cell is proposed and is found to have good performance in harmonic compensation, load balancing, and neutral current compensation [11]. Bhaskar et al. have found STATCOM/Fuel-cell to be effective in improving voltage stability when there is additional load in the system as well as improving transient stability by reducing the fault clearing time after a fault is introduced into the system [12]. While integration STATCOM with fuel cells have been proven to improve its performance on transient stability, the studies did not evaluate the performance of an integrated DSTATCOM/Fuel-cell system on the improvement of voltage fluctuation and flicker caused by PV power output fluctuation.

This paper presents a model of an integrated DSTATCOM/Fuel-cell for the mitigation of voltage fluctuation, flicker and PV power output fluctuation. A PI-based controller is used for manipulating the real and reactive power output for power and voltage regulation respectively. The performance of the proposed system on a typical Malaysian distribution network with a grid-connected PV system is evaluated using MATLAB Simulink. Results indicate that DSTATCOM/Fuel-cell is more effective than DSTATCOM and can regulate the voltage at 1.0 p.u. and mitigate flicker levels up to 83%.

2. Modelling of Malaysian Distribution Network, PV system, DSTATCOM/Fuel-cell and control scheme

A simulation model of a typical Malaysian Distribution Network was modelled using MATLAB Simulink. The model is a three-phase four wire system consisting of a 33/11 kV transformer, an 11/0.4 kV transformer, and a low voltage (LV) lumped load which is used to represent all loads on the LV feeders as shown in Figure 1. A 100-kW grid-connected PV system and a DSTATCOM were modelled and connected at the point of common coupling (PCC). The technical specifications for the transformers, cables, and PV system are shown in Table 1 and Table 2 respectively. Figure 2 shows the schematic diagram of the proposed three-phase DSTATCOM with integrated fuel cell system which consists of a voltage source converter (VSC), a DC link capacitor, a control system, and a 100-kW fuel cell array. The fuel cell array parameters are shown in Table 3.

**Figure 1.** Diagram of the distribution network.**Figure 2.** Diagram of the proposed system.**Table 1.** Transformer and cable technical specifications.

Transformer			Cable			
Voltage	Rating	Vector Type	Type of Cable	Length	Resistance (at 50 Hz at 90 °C)	Reactance (at 50 Hz)
33/11 kV	3 MVA	Dyn11	300MMP 4C XLPE Al	200 m	0.13 ohms/km	0.072 ohms/km
11/0.4 kV	750 kVA	Dyn11	70MMP 4C XLPE Al	80 m	0.568 ohms/km	0.075 ohms/km

Table 2. PV system specifications.

Module	Rated Power	Total number of modules	Number of parallel strings	Number of series-connected modules per string
SunPower SPR-415E-WHT-D	100 kW	238	34	7

Table 3. Fuel cell specifications.

Fuel cell type	Capacity	Number of cells in a stack	Nominal voltage	Nominal current	Stack efficiency
PEMFC	100 kW	2	625 V	160 A	55%

Figure 3 shows the control scheme for the DSTATCOM/Fuel-cell model. There are two main objectives for the control scheme, to regulate power flow using real power and to regulate voltage using reactive power.

The three-phase voltages and currents at the terminals of DSTATCOM, V_{abc} and I_{abc} , were measured and converted to d-q components using Park's transformation. The instantaneous real power, $P_{dstatcom}$, was calculated from the d-q components of the voltage and current as in equation (1).

One of the main control objectives is to perform voltage regulation at the PCC by using reactive power compensation. A PI controller was used to calculate the reference reactive current, $I_{q/ref}$, based on the error between V_{abc} and its reference, $V_{abc/ref}$.

Another control objective is to regulate the power flow into the grid by using real power compensation so that the total power supplied to the grid is constant and not fluctuating. Hence, the reference for power supplied to the grid, $P_{tgrid/ref}$, was specified to be the same as the rated power of the PV system. The reference of the DSTATCOM real power output, $P_{dstatcom/ref}$, is the difference between the PV power output, P_{pv} , and reference power, $P_{tgrid/ref}$. A PI controller was used to calculate the reference real current, $I_{d/ref}$, based on the difference between the measured DSTATCOM power output, $P_{dstatcom}$, and the reference DSTATCOM power output, $P_{dstatcom/ref}$.

The real and reactive currents, I_d and I_q are processed through PI controllers to obtain outputs $V_{d/ref}$ and $V_{q/ref}$. The modulation index, ρ , and modulation angle, α , is calculated from $V_{d/ref}$ and $V_{q/ref}$ as in equation (2) and equation (3) respectively and is fed to the VSC.

$$P_{dstatcom} = \frac{3}{2} \times (V_d \times I_d + V_q \times I_q + 2 \times V_0 \times I_0) \quad (1)$$

$$\rho = \sqrt{V_{\text{d/ref}}^2 + V_{\text{q/ref}}^2} \quad (2)$$

$$\alpha = \tan^{-1} \frac{V_{q/\text{ref}}}{V_{d/\text{ref}}} \quad (3)$$

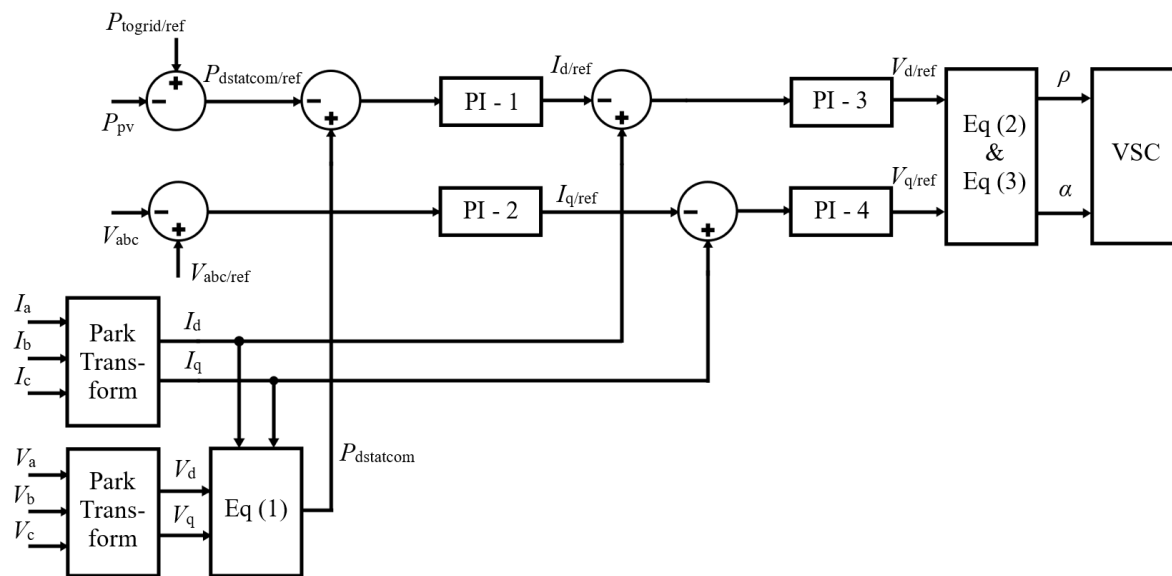


Figure 3. Block diagram of the controller.

3. Simulation Results

The studies were simulated under three different circumstances, (i) no mitigation method, (ii) with 100-kVAr DSTATCOM, and (iii) with 100-kVA DSTATCOM/Fuel-cell. Figure 4 shows the voltage measured at PCC under these three conditions. In Malaysia, the steady state voltage level fluctuation limits are +10% and -6% of 400 V [13]. From the results, in all three cases, the voltage fluctuation is still within the statutory limits. However, when no mitigation method is used, the voltage level fluctuations between 0.973 to 0.986 p.u. and the installation of DSTATCOM to the network managed to reduce the voltage fluctuation to between 0.994 to 1.0 p.u. The system voltage is further improved and maintained at a constant 1.0 p.u. when DSTATCOM/Fuel-cell is connected.

Figure 5 shows the total power output into the grid after power flow regulation by DSTATCOM/Fuel-cell compared with the PV power output without power flow regulation. From the results, without power flow regulation, the PV output power has a very high degree of fluctuation. When DSTATCOM/Fuel-cell is connected, the system manages to regulate and mitigate the fluctuation of power flow into the grid by injecting real power to compensate for the fluctuating output power from the PV system.

Table 4 shows the flicker severity index measurement for the three cases stated above. The absolute short-term flicker severity (P_{st}) as described in IEC 61000-4-15 standard is used to evaluate the flicker levels [14]. According to the TNB Energy Supply Application Handbook, the P_{st} value should be less than 1.0 for voltages 132 kV and below at the PCC [13]. From the results, the P_{st} value of the network without any mitigation method exceeds the statutory limit. When DSTATCOM is connected to the network, the P_{st} value is reduced by 36% and drops to within the statutory limit. However, it is still relatively high and is close to the statutory limit. When DSTATCOM/Fuel-cell is connected, the P_{st} value is reduced by 83% as compared to the network without any mitigation method and is well below the statutory limit.

By reducing the flicker levels, issues such as premature failure in electric motors due to voltage flickers and flickering in computer screens can be avoided. Thus, the maintenance costs of air conditioners in residential areas and equipment with electric motors in industrial areas can be reduced. Health issues caused by people working on flickering computer screens can also be prevented and therefore increase productivity in the workplace.

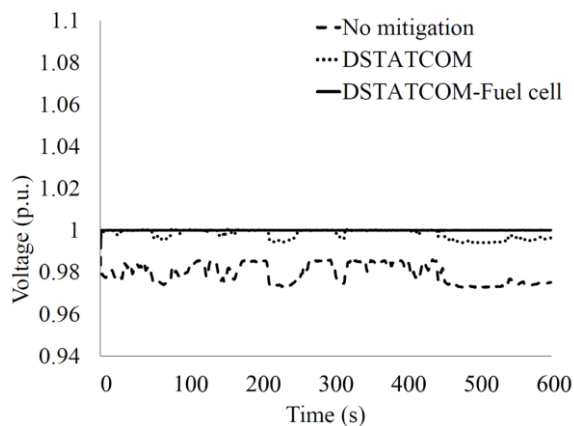


Figure 4. Voltage at PCC.

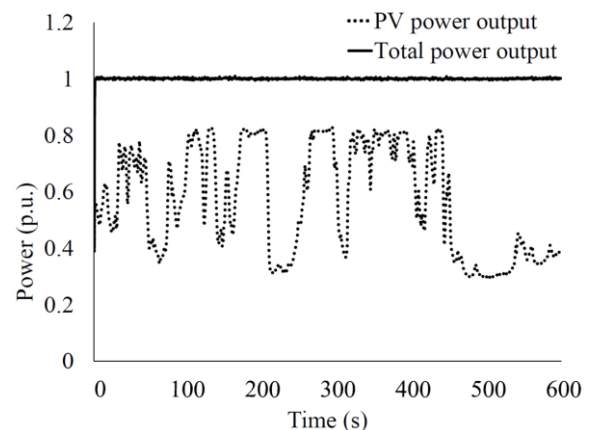


Figure 5. Output power flow regulation.

Table 4. Flicker severity index.

Absolute Short-Term Flicker Severity (P_{st})			
Statutory limit	No mitigation	DSTATCOM	DSTATCOM/Fuel-cell
1.0	1.290	0.8180	0.2132

4. Conclusion

In this paper, a distribution static synchronous compensator integrated with fuel cell is proposed to mitigate voltage fluctuation and flicker which are caused by the high penetration of photovoltaic systems onto the distribution grid. The proposed method uses a combination of real and reactive power compensation to perform power flow regulation and voltage regulation respectively. The performance of the proposed system is evaluated by connecting it to a distribution network with a grid-connected photovoltaic system. Results show that by integrating a fuel cell with the distribution static synchronous compensator, the voltage flicker mitigation performance of the system is improved by 83% and 36% respectively. Voltage fluctuation is negligible when using the proposed system whereas there still exists some degree of voltage fluctuation when using only a distribution static synchronous compensator.

Nevertheless, a cost comparison analysis of the proposed system which uses fuel cells with respect to other energy storage systems such as batteries is required to determine the economic viability of using fuel cells instead of batteries. Additional studies are also needed to compare the performance of fuel cells with batteries when integrated with a distribution static synchronous compensator for power quality improvement on photovoltaic systems.

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