PV System Based Dynamic Voltage Restorer (DVR) in Water Pumping System for Agricultural Application

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ABSTRACT

Modern solar-powered pumping systems are already being utilized in various fields and industrial applications especially in agricultural water irrigation systems where pumping water at a remote location is required with fewer electricity accessibility from the grid is not feasible. PV solely depends on solar hours per day, and it is not reliable when a location exhibits variable weather conditions, such as in Malaysia, having 12 solar hours daily but maximum 5-6 peak performance hours are as usually achieved due to the cloudy and rainy nature of the weather. In this case, PV-grid is not able to generate power as per daily demand and would create voltage sags, swell, and power outage when it is directly connected with the water pumping system for irrigation. To overcome this problem, a PV-DVR solar water pumping system (PV-DVRWP) is proposed in this paper that can mitigate power quality issues

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arising from PV-grid side such as voltage sags, voltage swells, and power outage by injecting the required amount of voltage into the line to maintain constant load voltage supply. The DVR controller strategy uses dq-abc frame mechanism to extract fault signals by using Park's transformation method, PID, and hysteresis band PWM signal generator to drive the inverter of DVR connected with a battery storage system. The proposed methodology of the PV-DVRWP system mitigates power quality issues occurring from the PV-grid side by injecting compensating voltage as well as being able to support water pumping systems in case of power outage for a three-phase system.

Keywords: *Renewable energy; Dynamic Voltage Restorer; Solar water pumping system; Power quality issues; PV-Grid; PV irrigation system*

Introduction

Modern solar water pumping systems are field-proven methods providing water pumping aid in locations where grid-connected pumping systems are not reliable or easily accessible. Photovoltaic (PV) based solar cells are used in these systems that convert sunlight into electric power to operate the DC/AC motors to drain the groundwater or surface water pumping systems [1].

This case study covers a procedure design for the Malaysian agriculture and irrigation system upgrade by the solar-powered water pumping system. Due to the rapid increase in diesel/fuel costs, the energy demand by farmers in Malaysia is facing severe difficulties in irrigating their crops under such circumstances [2, 3]. An alternative facility is required to fulfill the need of farmers to power the water pumping systems in an economical way that can bring revolution in agriculture and provide energy independence whilst solar pumping systems are key to it [4, 5, 6, 7].

This paper outlines the application of a dynamic voltage regulator (DVR) with a solar water pumping system and demonstrates the potential advantages of this method. DVR is a series active power filter device that is used to protect sensitive loads from power quality issues such as voltage sag, swell, harmonics, or disturbances [8]. Though, the main objective of the solar-powered irrigation system design is to meet the intended water requirement through cost-effective and proper selection of different systems and components. Solar-powered water pumping systems are like any other pumping system, where the power source is solar energy i.e., by the Photovoltaic (PV) panels. A conventional solar pumping system may consist of a PV array to power the water pump motor usually used to extract water from the ground or stream (river) to fill up water storage tanks. So that gravity feed is used to irrigate without any external energy system. PV-based water pumping systems are cost-effective and alternatives to agricultural wind turbines for remote area water supply [9, 10].

Solar power is less ideally used to run heavy machinery such as AC motors for pumps that roughly require 100,000 times more power consumption than a PV cell generating small DC power. Therefore, batteries are usually used with PV systems to provide some means of storing energy. An inverter is used to convert DC power from the PV array and battery into AC power. However, the phenomenon of converting DC to AC and storing energy to the battery by PV array is not that efficient therefore a further 10% margin must be added to the required array size. A complete solar power system is expensive to install and its power generation by PV array is controlled by MPPT technique that generates maximum power and regulates the voltage to operate the motor smoothly [11]. Figure 1 shows the block diagram of a typical solar-powered water pumping system.

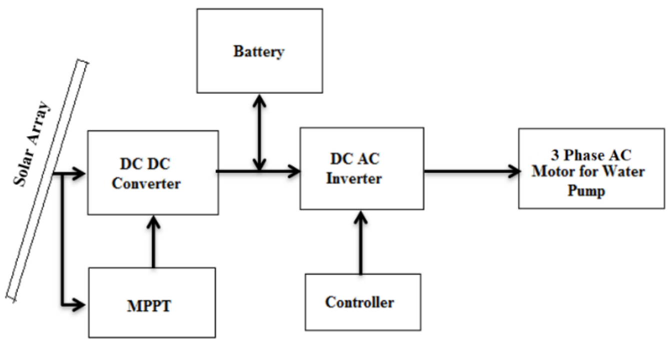

Figure 1: Solar-powered water pump motor system.

The scope of using renewable energy applications is increasing rapidly in past decades. They are being used in simple applications or in certain fields where solar energy is utilized extensively in each field [12]. Where agriculture has captured its advantage by using solar energy for the benefit and profiting of both the farmers and the environment. By replacing fossil fuel as a source of energy in the farms, solar energy helps to keep the environment clean and healthy by reducing the bad emissions as well as the noise generated. Also, it helps the farmers to be more self-dependent and make more revenue by reducing the costs of energy and the cost of maintenance [13].

Agricultural/irrigation improvement by solar powered pumping system

Solar pumping systems are ideal to implement in remote locations where grid-based electricity reach is not available or limited. The solar-powered pumping system can only be justified if it is properly designed and linked with high-efficiency irrigation systems such as drips, bubbler, sprinkler, or bed and furrow irrigation methods [14].

The usage of Malaysian agriculture total water consumption is about 68% of total water although the irrigation efficiency in larger irrigation schemes is 50% and less than 40% in the smaller ones [2]. The majority of developing and under-developed countries' economies are mainly dependent upon its agriculture and the continuous energy supply at an affordable price is the major factor affecting the agricultural sector. Energy crises countries are struggling to conceive conventional energy sources to support their agricultural sector that affects the corps water requirements in the irrigated areas and almost entire irrigation requirements within the rainfed areas are dependent on water pumping. Therefore, solar energy sources are highly considered to minimize the energy crises as estimated in [15]. Hence, by exploiting solar energy effectively in the agricultural sector it can increase its productivity and help to improve the environment as well.

Potential benefits of solar-powered irrigation system implementation

The solar-powered agricultural systems are capable to reduce operational cost as compared with direct grid-connected pumps by providing easy operational methods as compared with conventionally fuelled pumping systems as it, (i) generates uninterrupted energy for pumping systems daily for about 5-10 hours, (ii) provides flexibility of direct coupling or through batteries for irrigations purpose, (iii) supports as free energy source for remote watershed and rainfed areas, (iv) withstands long working life, (v) integrates with different drip, bubbler, micro-sprinklers and rain guns, (vi) stabilizes the climate due to no emissions of greenhouse gasses during irrigation process, (vii) responses swiftly towards the water flow requirements according to the weather conditions as in summer the water is needed at higher scale or else vice versa for winter periods, (viii) pumps in wide ranges to suit different farm sizes and socio-economic conditions and (xi) assures small payback periods, particularly if high-value crops is grown [16]. Other main applications of solar energy in agriculture are crop and gain drying space, water heating, greenhouse heating, and remote electricity supply (PV). Each of these systems has its own benefit for a specific use and purpose as given in [17].

Evolution of Solar Power Water Pumping System Applications

In the last decades, the issue of using PV cells for water pumping has been discussed and reviewed from different aspects. PV technology usage in water pumping is considered a very good alternative for conventional pumps which use fossil fuels. The importance of using renewable energy resources is suggested by [18] after considering the fact that the oil reserves are limited and the electricity cost is high. The acceptance of PV performance and reliability in remote areas for water pumping has increased significantly for many reasons. Firstly, unlike the limited availability of electricity grid connections, solar energy is available almost everywhere. Also, it is very reliable and can stand difficult weather conditions such as snow and ice [9].

However, solar technology requires different sets of expertise for installation, operation, and maintenance, since it has electrical, mechanical, and electronic components. There are other constraints such as the overall cost and energy storage. The main components in the PV water pumping system are solar PV array, charge controller, pump controller, batteries, inverter, Motor, storage tank, mounting structures and wiring, and discharge tubing or piping. PV pumping systems can be classified based on four main configurations such as energy storage, input electric power, type of pumps, and sun-tracking. Furthermore, solar-powered water pumping systems can be configured into two types, battery coupled and direct-coupled [19].

PV water-pumping systems (PVWPs) are reliable and becoming much cheaper due to inexpensive PV modules. PVWP systems prices have dropped by 2/3rd as compared to fuel prices which have risen >250% since 2000. These systems are durable and are operational for a long period such as the one installed in Estacio Torres in Sonora Mexico is operating for more than 20 years. PVWPs off-the-shelf capabilities have grown to 25 kW and are expected to exceed 100 kW. PVWPs global sales are steadily growing and approaching 100,000 systems per year. PVWPs are becoming a choice for millions of small farmers/ranchers due to its reliability and affordability with increased agricultural productivity around the globe. Whereas the productivity of irrigated land is approximately three times greater than that of rain-fed land [20].

Most of the developing countries face issues of power interruptions or blackouts because the generated electrical power is less than the power in demand. Therefore, consumers face power quality issues due to voltage sag, short-duration voltage swell, and long duration power interruption [21]. Dynamic voltage restorer (DVR) is a cost-effective solution to mitigate voltage sag and voltage swell, conveniently. It is also able to withstand long-term power outages by injecting the required voltage quality level for the sensitive loads when connected with an energy storage device [8]. The limitation of the DVR system proposed by [21] is that it can recover sags up to 10% of source voltage only and the PV-DVR system is focused to mitigate the distribution system only.

SolarVest Malaysia stated that the efficiency of solar energy generation is dependent on the weather condition, which drops consequently due to the cloudy and rainy weather nature of Malaysia [22]. PVWPs would not run effectively due to the variability of solar energy. Therefore, DVR is proposed in PVWPs to mitigate voltage sag and voltage drops caused by PV systems in absence of sunlight. The aim of this research is to develop a DVR-based solar-powered water pumping system for agricultural irrigation systems to continuously supply constant power for the pump. The pumping system shall be designed to meet the intended water requirement through cost-effective means by careful selection of different systems and components. However, the design criterion for the solar-powered irrigation system is based on:

i. The peak water requirements.
ii. The lowered solar energy availability in a year of time, so if water needs are fulfilled during the lean solar time, it will ensure peak water needs when solar energy availability is at maximum.

Design Consideration and Methodology

The estimation of water demand is an important factor to be considered before the design. Therefore, a precise calculation is required to set up the operation of the pumping system up to the scale. For example, in our project case, the solar system irrigates a cropped field. Therefore, the demand of water required, size of the field, and type of crop must be known. Table 1 shows the water demand in millions cubic meters (mcm) for the year 2010 and the projection of water demand by the year 2050 in the agricultural sector of Malaysia [23]. However, for full water irrigation system design, the peak water requirement should be estimated to develop the solar water pumping system.

Table 1: Estimation of yearly water requirement for the agricultural sector of Malaysia [23]

Water Demand		mcm / year	
		2010	2050
Agriculture Sector		9,512	8,959
a.	Paddy (irrigation)	8,266	7,205
b.	Non-Paddy Corps	1,117	1,176
c.	Livestock	126	578

Rice paddy field water irrigation system is selected in this study for the Penang state of Malaysia, as it is one of the most water-deprived regions during paddy field season with the water withdrawal requirement of an average of 2788 mm^3 per season. Paddy field season in Malaysia starts from March/April till mid-May (estimated about 40 - 105 days). The irrigation water requirement for 1.82 hectares of paddy field is 755 mm/season [23, 24]. Therefore, the daily water needed estimated for the paddy field is about 3 mm/day for a minimum field size of 1 acre.

Malaysia has the potential to have an average of 12 hours of sunshine daily [25]. However, due to variable cloudy weather conditions of Malaysia, the maximum performance achieved by solar hours is about 6 hours of daily sunshine with 250 days of water pumping system operation per year, are considered.

The PV water pumping system is designed to provide power supply for agriculture loads such as centrifugal water pumps operating 5 hours daily. The system is to be installed in a small farmhouse to support a ¼ acre of paddy field to pump about 317.5 gallons (1.202 m^3) of water per day for a remote region. A three-phase water pump motor is used with the following specifications: 2.5 kW, 415 V, 6 A, 2850 rpm, and 50 Hz. The system is designed to provide energy source through PV system connected with the grid and as well as runs the pump from stored energy from batteries by a DVR system during the times when sunlight is not efficient or in cloudy weather.

Single-crystal silicon cells (c-Si or mono-Si) array is selected for the proposed application to run the pump motor due to its reason of limiting the cost reduction. c-Si is an indirect band-gap semiconductor with 1.1 eV and with a much smaller absorption constant as compared to direct band-gap materials. 33 to 36 individual cells are connected in series in a PV array. Individual silicon cell open-circuit voltage ranges from 0.5-0.6 V depending upon irradiance level and cell temperature which results in a module having an open-circuit voltage between 18 V to 21.6 V. Whereby, the cell current is directly proportional to the irradiance and the area of a cell [26]. Thus, for the one-acre (4046.86 m^2) of land, a PV module of size 4 ft^2 (0.372 m^2) is proposed with an active cell area expected to produce a maximum power of 55 W at approximately 17 V and 3.2 A under direct sunlight.

The block diagram of the proposed photovoltaic DVR water pumping system (PV-DVRWP) is illustrated in Figure 2. In this case a 100 kW PV array is connected to the utility grid which is also connected to the water pumping system. In this process, the water pump is operated by either grid or PV system. However, whenever the PV-Grid efficiency is low it will create voltage sag, long-term voltage interruption, or outage. To mitigate the voltage sag DVR is activated and injects the required amount of voltage into the system to maintain constant and smooth power, delivered to the water pump motor.

DVR works as a power quality conditioner to compensate for power quality issues coming from the source side [8]. PV-DVR system consists of a source side PV array connected to a booster converter that regulates the PV array voltage at 500 V in accordance with the MPPT controller. PV inverter converts the incoming DC voltage to AC voltage (260 V) that is further boosted by the step-up transformer converting low AC voltage to high AC voltage (25 kV), to feed the excessive solar energy generation into the utility grid. Table 2 shows the parameters used to set up the PV array in Matlab-Simulink.

A second step-down transformer is used to convert High-Voltage to Low-Voltage (415 VAC), to match the load capacity of the water pump three-phase AC motor. In a DVR system, a DC energy source (a battery in this case) is connected with the inverter that is able to convert DC voltage to AC voltage and injects the compensation AC voltage into the distribution line by an injection transformer through the passive filter. The DVR parameters are given in Table 3.

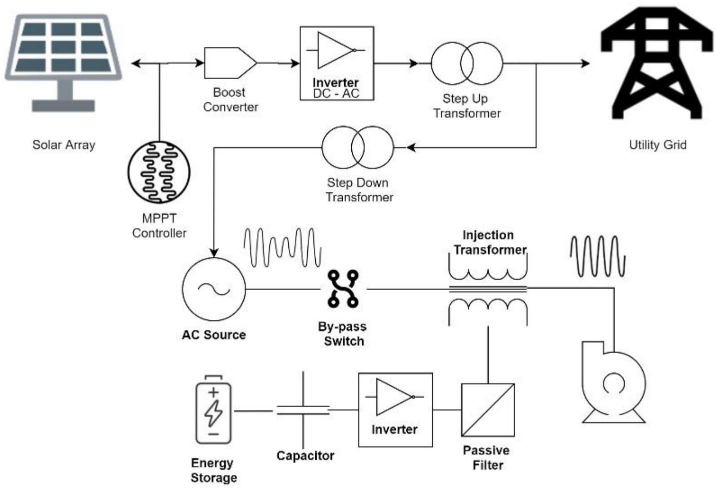

Figure 2: PV-DVR water pumping system (PV-DVRWP).

Table 2: Parameters of PV Array

Module	Apollo Solar Energy ASEC-305G6s
No. Cell per Module	72
Max. Power (W)	305.019
Open circuit voltage V_{oc} (V)	35.55
Voltage at max. powerpoint V_{mp} (V)	35.55
Short Circuit current I_{sc} (A)	8.99
Current at max. powerpoint I_{mp} (A)	8.58

Table 3: Parameters of DVR

Input Source from Utility Transformer	5 kV, 50 Hz
Unbalanced Load	3.7 kW or 5 HP Machine
3-Phase Coupling Transformer	10 MVA, 50 Hz, Winding Ratio: 5:8
Winding 1 - Ripple Filter	R= 60 Ω; C = 100 mF
Passive Filter	L = 200 mH
Switching Filter: Capacitor	1 µF
Voltage Source Inverter	3 arms; 6 pulses
Carrier Frequency	5 kHz
Battery	800 V
DC-Link Capacitor	10 mF

The DVR controller block diagram is shown in Figure 3, it is designed to work on the following principles, (i) generation of a fixed reference voltage, as expressed in Equation (1), (ii) detection of imbalance voltage in the system by using Park's Transformation as given by Equation (2), as *dq* components, and then converting *abc-to-dq0* frame system, (iii) reference voltage generation by coordinate transformation method, vi) comparison of imbalance voltage with the constant sine wave reference voltage as given by Equation (3), (v) two PID controllers with a feedback signal to extract control gain signal to transform *dq0-abc* frame system by inverse park transformation method as given by Equation (4) and (vi) furthermore, this signal is fed into hysteresis band voltage controller to generate gate pulse for DVR (inverter). Consequently, the *dq0-abc* frame control signal is generated as expressed by Equation (5).

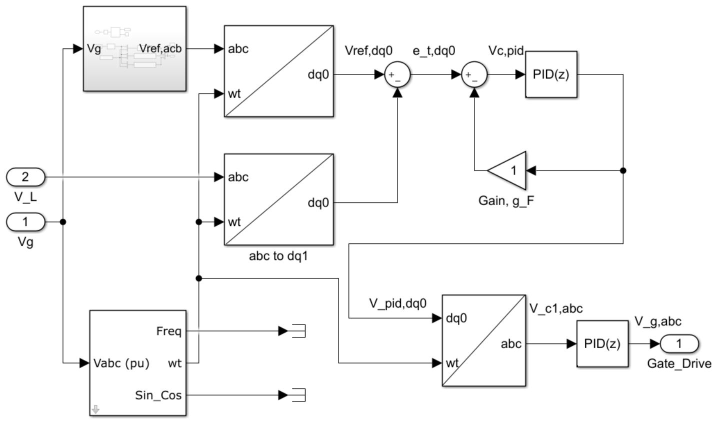

Figure 3: DVR controller strategy block diagram.

$$[V_{A,ref}\ V_{B,ref}\ V_{C,ref}\ ] = V_{f.ref}\left[sin\omega t\ sin\left(\omega t - \frac{2\pi}{3}\right)\ sin\left(\omega t + \frac{2\pi}{3}\right)\right] \quad (1)$$

$$[V_d\ V_q\ V_0\ ] = \frac{2}{3}\left[cos(\omega t)\ cos\left(\omega t - \frac{2\pi}{3}\right)\ cos\left(\omega t + \frac{2\pi}{3}\right)\ - sin(\omega t)\ - sin\left(\omega t - \frac{2\pi}{3}\right)\ - sin\left(\omega t + \frac{2\pi}{3}\right)\ \frac{1}{2}\ \frac{1}{2}\ \frac{1}{2}\right] \times [V_a\ V_b\ V_c\ ] \quad (2)$$

$$|e_{t,dq0}| = \sqrt{\left(V_{ref,d} - V_{L,d}\ \right)^2 + \left(V_{ref,q} - V_{L,q}\ \right)^2 + \left(V_{ref,0} - V_{L,0}\ \right)^2} \quad (3)$$

$$[V_{c1,a}\ V_{c1,b}\ V_{c1,c}\ ] = \left[sin(\omega t)\ cos(\omega t)\ 1\ sin\left(\omega t - \frac{2\pi}{3}\right)\ cos\left(\omega t - \frac{2\pi}{3}\right)\ 1\ sin\left(\omega t + \frac{2\pi}{3}\right)\ cos\left(\omega t + \frac{2\pi}{3}\right)\ 1\ \right] \times [V_{c1,d}\ V_{c1,q}\ V_{c1,0}\ ] \quad (4)$$

$$V_{g,abc} = K_p V_{c1,abc} + K_i \int_0^1 V_{c1,abc} dt + K_d \frac{dV_{c1,abc}}{dt} \quad (5)$$

Results and Discussion

Matlab/Simulink is used to simulate the proposed system to determine the performance of the DVR system connected with a battery and a PV water pumping system for mitigating voltage sags, swells, and outages. A PV-grid connected system with DVR Water Pumping system (PV-DVRWP) is shown in Figure 4.

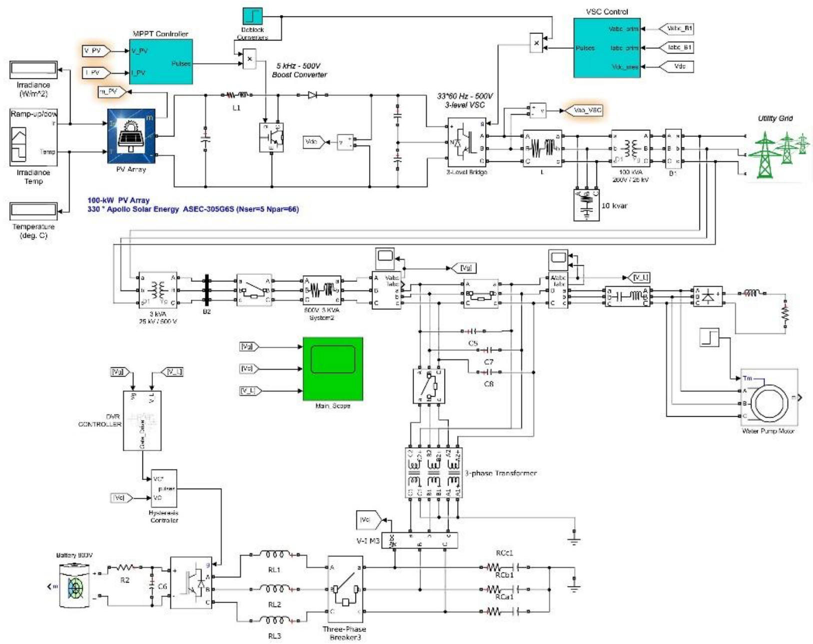

Figure 4: PV-DVRWP system.

<u>Case I: balanced voltage sag</u>

Figure 5(a) shows a 30% balanced voltage sag occurs from the source side when the demand of electrical energy is increased by the utility while the PV grid is operating at low irradiance sunlight condition, at time intervals from t = 0.1 s to t = 0.6 s. Voltage recovery mode is initiated as soon as the DVR controller detects the voltage loss in the system and injects the required amount of voltage to mitigate the voltage sag, as shown in Figure 5(b). The improved load voltage condition with mitigated balanced voltage sag is shown in Figure 5(c), assuring the performance robustness of the DVR. As compared with the system presented in [21], the proposed DVR can mitigate more than 10% of voltage sag errors.

<u>Case II: balanced voltage swell</u>

When voltage swell happens in the PV-Utility grid, the DVR should activate its operation by absorbing the power from the grid. Figure 6(a) shows a 15% balanced voltage swell that occurs from t = 0.1 s to t = 0.6 s. DVR detects the incoming exceeded voltage from the source side and injects the voltage with 180^{o} shift but in phase with system voltage, which is subtracted from the excessive voltage magnitude, as given in Figure 6(b). However, once the voltage stabilizes to its nominal limit the DVR shifts back to standby mode to maintain minimum conduction loss. From Figure 6(c) the DVR can maintain a load voltage peak closer to the nominal voltage limit. Whereas the proposed system can inject compensating voltage to mitigate more than 10% of voltage swell as compared with [21].

Case III: power outage

A total power outage can happen when the PV system is down and the utility feeder is at fault, hence producing zero voltage. In this case, the water pumping system can be disrupted. A short circuit fault in one of the feeders from the grid side will also affect the line causing balanced voltage sag. However, in this case, DVR is operated during power outages from the PV-grid side as seen in Figure 7(a), at intervals t = 0.1 s to t = 0.6 s. DVR can support the zero-volt error by injecting about 70% of nominal voltage into the system as shown in Figure 7(b). Figure 7(c) shows the load voltage profile after compensation. [21] presented a system that mitigates voltage disturbances in a single-phase system only. However, the proposed DVR system acts as a microgrid and is able to withstand longer and deeper voltage sags.

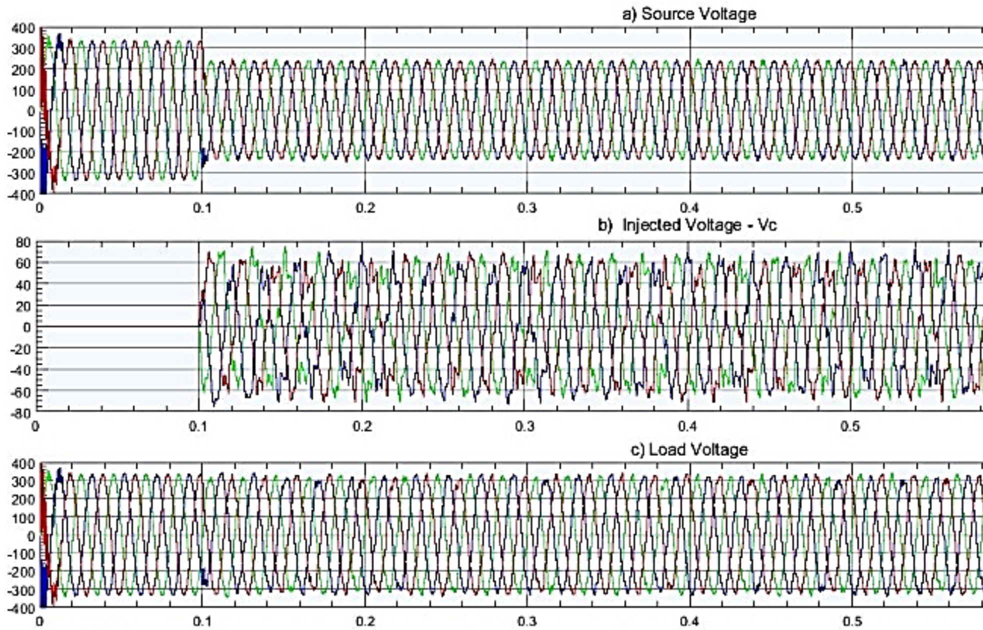

Figure 5: DVR in solving power quality problem with (a) balanced voltage sag of 30%, (b)
improved load voltage.

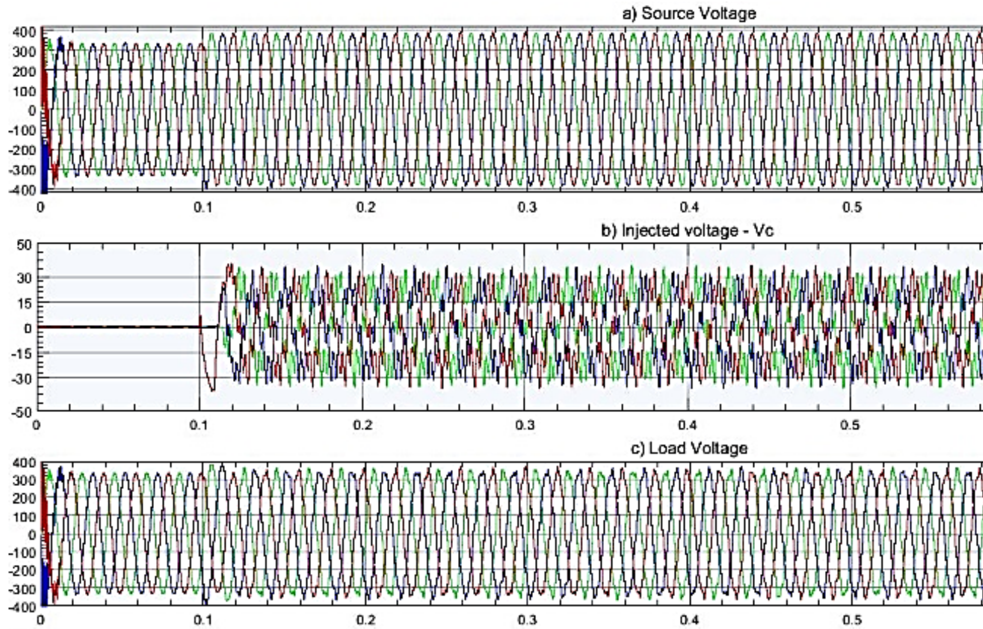

Figure 6: DVR in solving power quality problem with (a) balanced voltage swell of 10%, (b
improved load voltage.

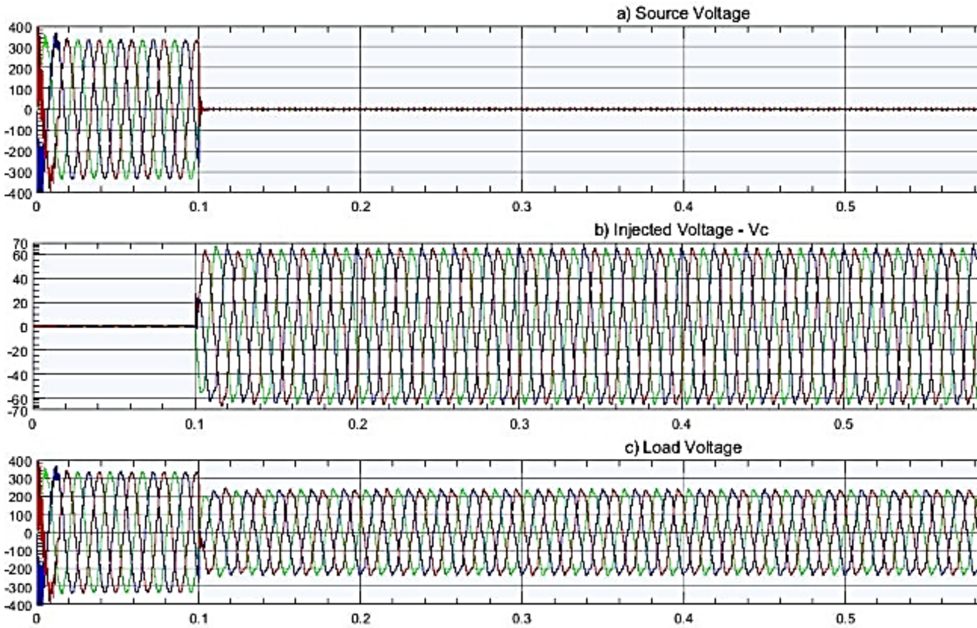

Figure 7: DVR in solving power quality problem with (a) Voltage Outage, (b) voltage injec
load voltage.

Conclusion

This paper discussed the use of DVR in the application of the Solar Renewable Energy sector used for irrigation purposes to mitigate power quality problems occurring from the PV grid-connected with a water pumping system for agricultural use. The results show that the proposed DVR system can mitigate power quality issues occurring from the PV-grid side by injecting compensating voltage in case of voltage sag and voltage swell as well as. It is also able to support water pumping systems in case of a power outage. This implies that the battery storage attached with DVR can support and deliver constant voltage during DVR operation mode for a longer duration.

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