Voltage Regulation in a Radial Microgrid with High RES Penetration

Approach-Optimum DVR Control

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Abstract-Increasing installation of Renewable Energy Sources (RESs) in microgrids and distribution system feeders benefits the power system in many ways, such as increasing power availability and reliability, but they also cause various power quality issues, such as overvoltage and undervoltage, due to their intermittent nature. The sensitive loads, such as Constant Power Load (CPL), are affected by these voltage fluctuations. The approach proposed in this paper is to install a Dynamic Voltage Restorer (DVR) adjacent to the RES to suppress the voltage issue caused by it while leaving the sensitive load operation unharmed. The proposed concept is duly endorsed with analysis and simulations in MATLAB/Simulink environment.

Keywords-DVR; intermittent RES; CPL; voltage regulation; microgrid

I. INTRODUCTION

Penetration of Renewable Energy Sources (RESs), such as solar, wind, hydro energy, etc. has been increased in the distribution systems due to increased demand, availability, and the environmental concerns caused by the conventional sources [1]. When the penetration is increased, a part of the distribution feeder needs to be controlled and monitored separately by the distributed system operator. This part of the feeder may be regarded as a microgrid [2-3]. The increased penetration of RESs and their independent control gives to the system many advantages, such as increased available power, lesser generation from conventional power sources, increased power reliability, etc.. However, the increased penetration of RESs in the feeder may give rise to some power quality issues, in which variation in voltage level due to the intermittent nature of the RES is of major concern, especially today, when many of the loads connected in the distribution system require constant power for their better operation and behave like Constant Power Loads (CPLs) [4-7]. The power consumed by a CPL remains constant regardless of the voltage at the point of common coupling. If the voltage drops, the current level rises and vice versa. When tightly regulated, power electronic converters such as dc/dc converters feeding a load such as a battery, or dc/ac inverters driven loads are presumed to be CPLs. Furthermore, switching power supplies, which are found in the majority of mobile systems and inverter-based motor drive systems, act in the same way as CPLs [3, 5-6].

The power requirement of these CPL loads is unaffected by voltage variations at the terminal. When the voltage at the CPL terminals is increased, the current demanded by these loads decreases, resulting in negative impedance characteristics as observed by the feeder. This type of CPL characteristic could exacerbate the voltage rise issue in the feeder. As the current requested by the CPL drops, the overall drop in the feeder lowers as well, resulting in a higher voltage at the CPL's terminal and greater current reversal towards the main grid source. These factors may reduce the voltage stability of the microgrid. If the number of such CPLs connected in the micro-grid increases, a cascading effect could occur, causing instability in the micro-grid/distribution feeder [8]. To minimize such issues, the voltage at the CPL terminals should be kept within tight restrictions, and be such that the RES intermittency has the least impact on CPLs. There are numerous devices reported in the literature that can be used to regulate voltage in the distribution system, including Dynamic Voltage Restorers (DVRs), Static Synchronous Compensators (STATCOMs), etc. [9-12]. A DVR is a custom power device that is connected in series with the line and injects/absorbs a series voltage. In this paper, a radial microgrid voltage regulation approach is presented, in which the DVR is situated near the RES, minimizing the issue produced on the CPL connected in the radial microgrid by the intermittent nature of the RES. The voltage at the DVR's terminals is regulated by injecting/absorbing a voltage in series with the feeder. The proposed method is backed up by analysis and is tested in Matlab/Simulink environment.

II. SYSTEM CONFIGURATION

Figure 1 depicts the system diagram for the grid-connected radial microgrid with CPL and intermittent RES. The RES unit comprised of an RES source such as a rooftop PV or a wind turbine and is connected to the micro-grid/distribution system via a Voltage Source Converter (VSC) that is connected to the feeder as a current source. The RES is placed very close to the

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CPL in order to witness and study the worst effects of RES intermittency. The DVR is installed adjacent to the RES, so that it can absorb extra power and provide a small percentage of power, if needed, to regulate the voltage. Batteries can be used to extend the DVR's regulatory and compensation limits [13]. The grid is represented by the source V_S, while the feeder impedance is represented by the Z_S. The feeder in consideration is a distribution type feeder with an R/X ratio of around 8 [14].

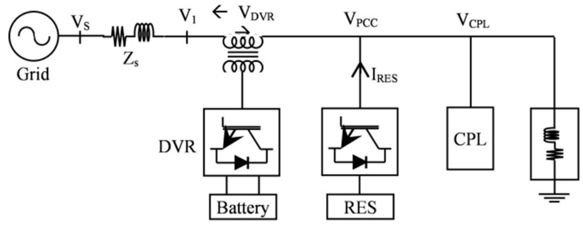

Fig. 1. Single line diagram of the considered system.

III. ANALYSIS OF THE CONSIDERED SYSTEM

The analysis of the considered microgrid system is conducted in two stages: At first, the impact of the RES on the CPL is investigated, and in the second stage, the way the existence of DVR may ameliorate the situation is investigated. The RES is considered to be situated very close to the CPL, and thus the feeder impedance between them can be overlooked.

A. Impact of RES on CPL

The equivalent circuit diagram for the considered system with only RES and CPL is shown in Figure 2(a). The Voltage at the terminals of CPL can be calculated with the help of superposition theorem and is given by:

$$V_{CPL} = \frac{Z_{CPL}(V_S+I_{RES}Z_S)}{Z_S+Z_{CPL}} \quad (1)$$

The impedance of the constant power load is dynamic in nature and can be written as:

$$Z_{CPL} = \frac{V_{CPL}^2}{P_{CPL}} \quad (2)$$

Equation (1) rewritten and simplified with value of Z_{CPL} obtained from (2) gives:

$$V_{CPL}^2 - V_{CPL}(V_S + I_{RES}Z_S) + Z_S P_{CPL} = 0 \quad (3)$$

If the RES current is known, then for a particular CPL load the voltage at the terminals of CPL can be estimated by solving (3):

$$V_{CPL} = \frac{(V_S+I_{RES}Z_S)\pm\sqrt{(V_S+I_{RES}Z_S)^2-4Z_S P_{CPL}}}{2} \quad (4)$$

B. With DVR Compensation Unit

In this stage the DVR is connected to the system as shown in Figure 2(b). The voltage at the terminal of RES can be regulated closed to the rated value through DVR. The voltage at the terminal of CPL obtained from (3) is taken into consideration for the estimation of the voltage to be supplied/absorbed by the DVR. The new voltage at the terminal of CPL after the insertion of DVR can also be estimated with the help of superposition theorem and is given by:

$$V_{CPL(New)} = \frac{Z_{CPL}(V_S+I_{RES}Z_S+V_{DVR})}{Z_S+Z_{CPL}} \quad (5)$$

After putting the value of Z_{CPL}, (5) can be rewritten as:

$$P_{CPL}Z_S + V_{PCC}^2 = V_{PCC}(V_S + I_{RES}Z_S + V_{DVR}) \quad (6)$$

If the voltage injected by the DVR is known, then the voltage at the terminals of the CPL can be calculated by solving the above quadratic equation. This equation can also be used in another way, for the estimation of voltage to injected/absorbed by the DVR as mentioned in (7).

$$V_{DVR} = \frac{P_{CPL}Z_S+V_{CPL}^2}{V_{CPL}} - V_S + I_{RES}Z_S \quad (7)$$

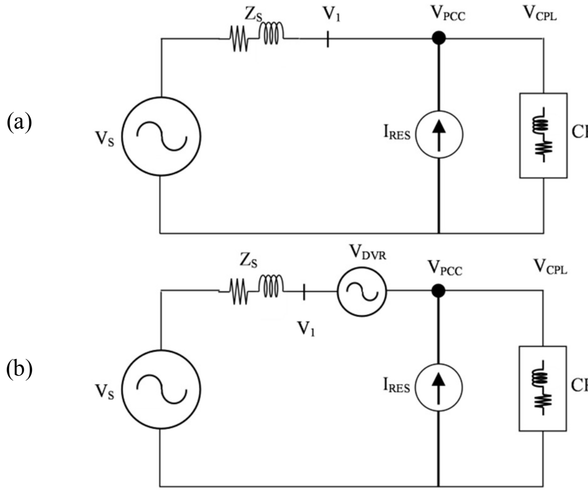

Fig. 2. Equivalent circuit diagram of the considered system (a) without any regulation from the DVR, (b) with DVR.

IV. CONTROL OF DVR

The control strategy for generating gating pulses of the voltage source inverter of the DVR is depicted in Figure 3. The synchronous reference frame theory is being used to control the DVR. The DVR injects or absorbs voltage in series to regulate the voltage at its terminal. It accomplishes this by sensing the voltage at the terminal, comparing it to the reference value of the voltage, and passing it to the Proportional Integral (PI) controller, which generates a voltage reference value for the quadrature axis (q-axis) component of the DVR. Initially, the DVR tries to keep the voltage underneath the range by using only the reactive component, resulting in only the q-axis component (V_q). However, if V_q reaches its maximum value, the q-axis component is reduced and the d-axis component is increased, resulting in a signal that may be used to estimate the voltage required to regulate the voltage with both d-axis (V_d) and q-axis (V_q) component at the DVR's terminal. To estimate the reference signal for the DVR's VSI, the reference d-axis and q-axis components are transformed into reference abc components via reverse parks transformation. To generate the gating pulse for the VSI switches, the reference signal is now routed through the pulse width modulator. The VSC then uses the obtained gate pulses to operate the switches.

V. PERFORMANCE EVALUATION OF THE PROPOSED SYSTEM

To validate the proposed concept, the considered system is simulated in MATLAB/Simulink. The simulation diagram of the system is shown in Figure 4. The system parameters used in the simulations are mentioned in Table I. To demonstrate the applicability of the proposed design, the system is tested under two conditions: (i) RES intermittency and (ii) load perturbation. For the sake of evaluation convenience, the initial transients that emerge in the simulation are ignored.

TABLE I. SIMULATION PARAMETER USED

Parameter	Parameter Values
Source/Grid Voltage	415V line to line
Feeder impedance	0.642+j0.083Ω/km [14], feeder length =0.5km
RES rating	10kW
CPL rating	3.75kW
Constant impedance load	2.5kVA to 7.5kVA, 0.8 pf lagging load
DVR rating	2kVA, maximum injection upto 100V

Figure 5 depicts the influence of RES intermittency on the voltage level in the microgrid and the ability of DVR to regulate the voltage during these intermittencies. RES injects a current of $I_{RESpeak}$ = 10A from t = 0 to 0.5s. Since the DVR is not injecting/absorbing voltage from t = 0 to 0.25s, the voltage observed (V_{CPL}) is lower than the rated value. The DVR is switched into the circuit at 0.25s, and the voltage at the DVR terminal is regulated to the rated value by injecting voltage (V_{DVR} = 71V) into the microgrid. Since RES penetration is low during this period, the DVR can regulate the voltage with only reactive power. The DVR is switched off at 0.5s, and the RES increased to more than double the initial value ($I_{RESpeak}$ = 20A) causing the voltage at the terminal of the CPL (V_{CPL}) to rise over the rated value, as shown in Figure 5 V_{CPL} (t = 0.5s to 0.75s). The DVR is turned on again at 0.75s, and this time it absorbs the extra voltage (V_{DVR} = 100V) to regulate the voltage at the CPL's terminal to the rated value. Since the DVR is unable to regulate the voltage using solely reactive power, therefore, both real (d-axis component V_d) and reactive (q-axis component V_q) components are used. Also, the DVR is absorbing the excess power in this case, so it can store it in the battery and use it whenever it is needed. The waveforms in Figure 6 are used to investigate the effect of a load connected at the feeder's end being perturbed. With I_{RES} = 10A, the penetration of RES is kept constant throughout the simulation. From t = 0 to 0.5s, the load connected at the end of the feeder is approximately 6.25kVA (3.75kW CPL load and 2.5kVA linear constant impedance load). The RES generates power that is close to the demand from local loads, therefore there isn't much voltage drop across the CPL load. The DVR can control the marginal variation from the rated value with the q-axis component only (V_{DVR} = 15V) from 0.25 to 0.5s. This is further supported by the zoomed waveform from 0.15s to 0.4s. From 0.5 to 1s, the load connected rises significantly with the CPL load remaining the same at 3.75kW, while the constant impedance load rose to 7.5kVA. As the local demand increased beyond the capacity of RES generation, the variation from the rated voltage rose significantly, requiring the DVR to regulate the voltage using a combination of real and reactive power with V_{DVR} = 100V, as shown in Figure 6 from 0.75 to 1s. This is backed even more by the zoomed waveform. As the DVR supplies real power into the system, it is depleting its real power stock that it had built up during the excess RES generation. As a result, the voltage at the CPL terminal is regulated.

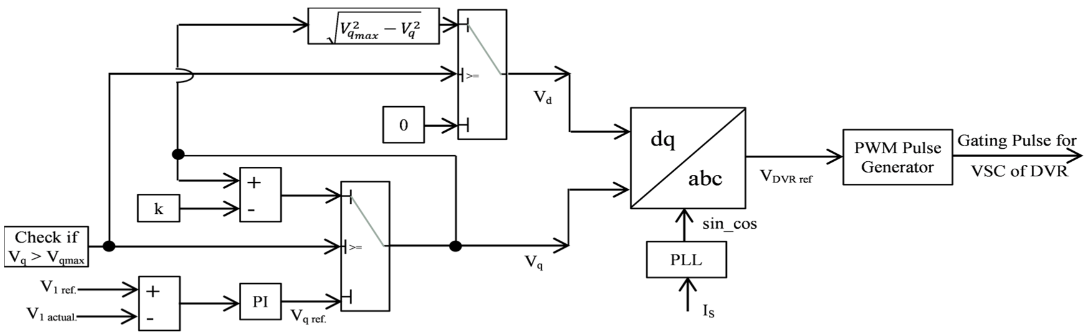

Fig. 3. Block diagram of the control scheme of the DVR.

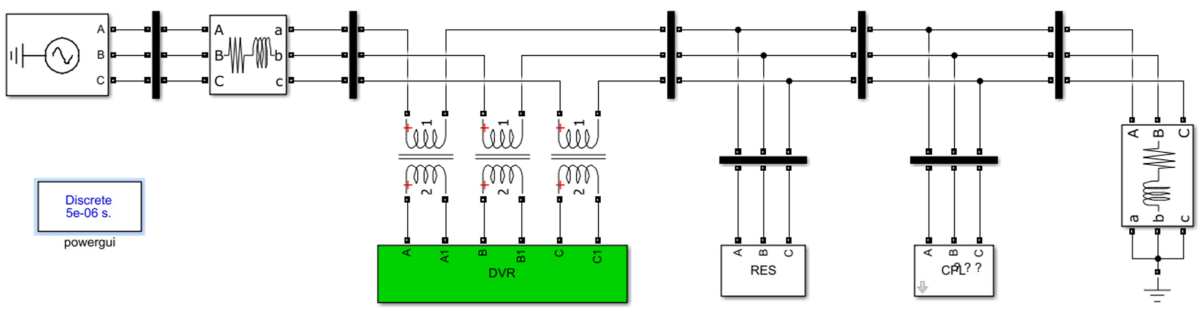

Fig. 4. MATLAB/Simulink simulation diagram of the system under consideration.

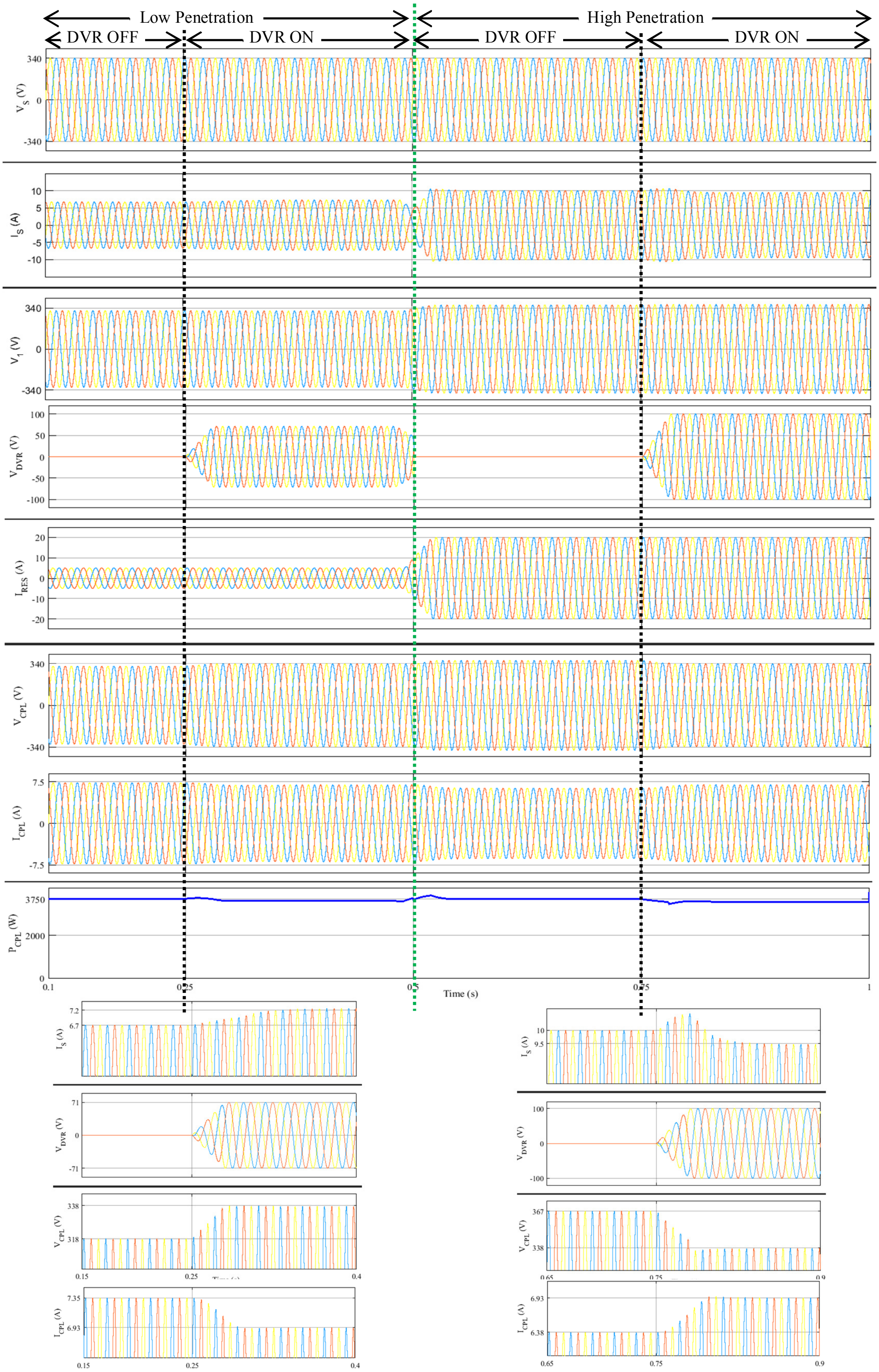

Fig. 5. Voltage and current waveform showing the efficacy of DVR during intermittency of the RES.

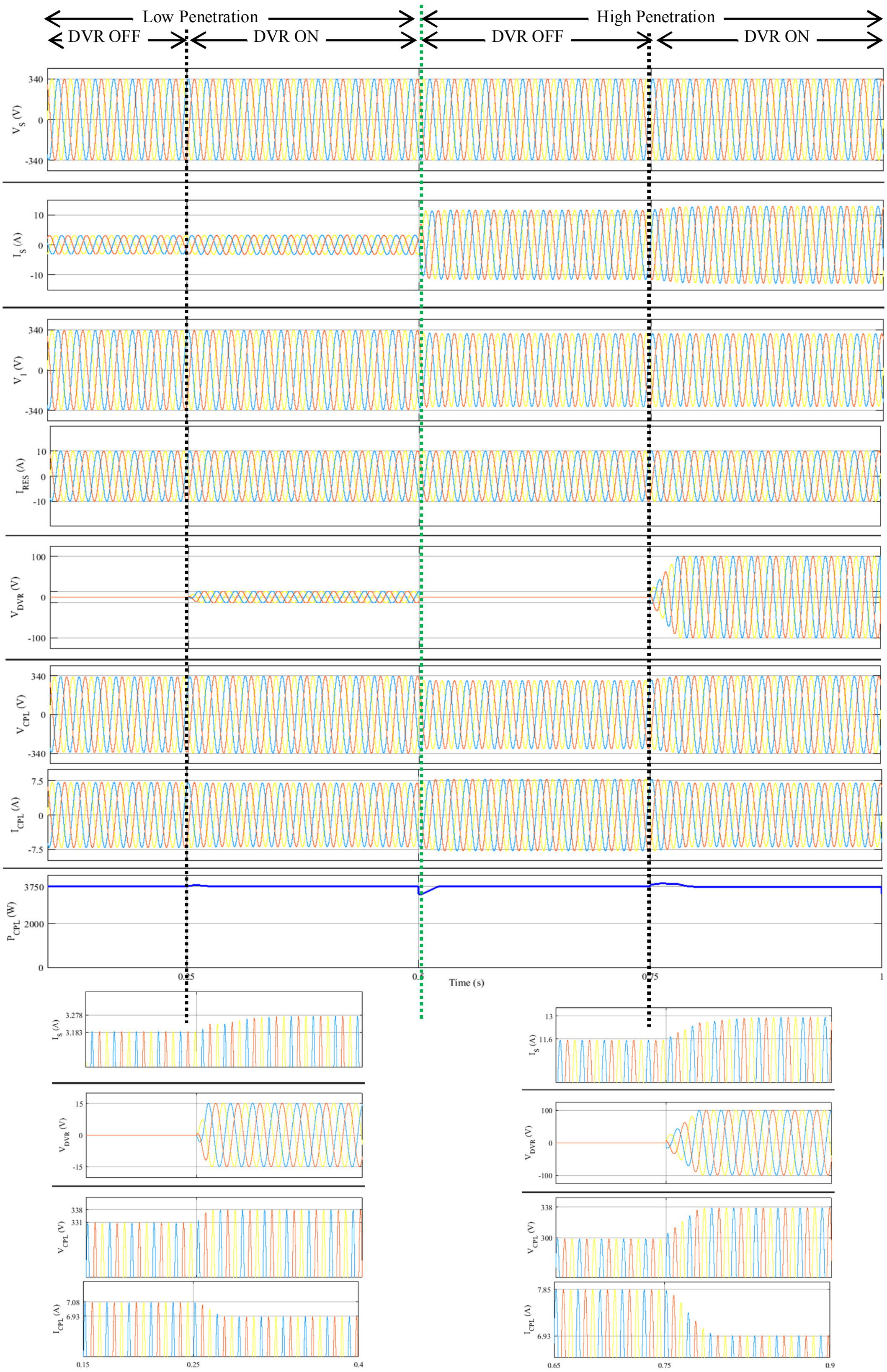

Fig. 6. Voltage and current waveform for showing the efficacy of DVR during load perturbations.

VI. CONCLUSION

In the presence of intermittent RES, voltage regulation in a radial microgrid feeding a sensitive CPL load has been investigated and demonstrated. Analysis was carried out to determine the value of the voltage at the CPL terminal in the absence of the DVR, as well as the value of voltage to be injected by the DVR. The Matlab/Simulink environment was utilized to simulate and control the proposed system. The simulation results for the intermittency of the RES source and the perturbation of load on the feeder were used to establish the performance of the DVR for voltage regulation. The demonstrated simulation results ensure that the voltage at the CPL terminal is relatively unaffected and settles in a short time. This allows the microgrid to benefit from greater RES penetration without compromising the operation of sensitive CPL loads.

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