PV-BASED DYNAMIC VOLTAGE RESTORER FOR POWER QUALITY ENHANCEMENT IN DISTRIBUTION SYSTEMS

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ABSTRACT

PV-based dynamic voltage restorer (DVR) is considered one of the most effective solutions for enhancing the functionality of the PV grid system by adding ancillary functions to the grid side inverter. DVR protects against voltage sag and swell based on pulse width-modulated (PWM) voltage source inverters. This paper investigates the performance and analysis of three phase DVR based on synchronous reference frame (SRF) theory. The control algorithm has been developed for the generation of compensating reference voltage vector to inject or absorb active and reactive power in series between the point of common coupling and critical load. The results presented in the paper show that the proposed control algorithm has excellent performance in both steady–state and dynamic phases.

INTRODUCTION

Recently, the increasing demand on clean and efficient energy across the globe [1] have motivated research work on finding more economical and environmentally friendly alternative energy generation systems. Renewable energy sources (RES) can play a significant role in the reduction of environmental problems and delay of fossil fuel depletion [2]. RES integrated at distribution level is termed as distributed generation (DG).

PV penetration as a DGs in low-voltage (LV) distribution networks has significantly increased. The PV uptake has been increasing with the growth of 60% per annum [3]. Therefore, with this range of high local PV power injections that normally coincide with low demand periods cause increasing incidence of over-voltage in the network based on current standards as reported in [4]-[6]. On the other hand, with the increased penetration of sensitive and non-linear loads, the power quality issues in the modern distribution system increased significantly [7].

Power quality (PQ) is one of the major concerns in the present era. Nowadays, a wide application of electronic devices in the industrial and medical centres has caused the power quality to be considered as one of the most important issues in the power system studies, particularly for the high-tech industries which use many sophisticated and sensitive equipment. Survey results suggest that 92% of the interruptions at industrial installations are voltage-sag related [8]. PQ costs due to the effect of voltage sags and swells account for almost 60% of the overall cost of industry. Sag is considered as the most serious problem of power quality [9]. Consequently, voltage stability becomes a pressing issue. According to the IEEE STD 1959-1995 and IEEE STD 1564-2014 (IEEE Guide for Voltage Sag Indices), voltage sag is defined as a decrease of 0.1 to 0.9 p.u. in the rms voltage at system frequency and of the duration of half a cycle to one minute [10]-[12].

Hence, increasing the functionality and ancillary functions for PV systems to mitigate power quality problems especially in modern electrical power system which dependent on RES has become a requisite. Actually, PV generation units in modern systems have achieved a high degree of reliability. Electric energy storage systems paved the way for mitigating power quality problems depending on RES. Moreover, increasing the dependency and functionality of the voltage source inverter (VSI) is substantial as the inverter and its control system are considered the main core of any grid connected PV system.

Dynamic voltage restorer (DVR) is one of the effective and direct solutions for “restoring” the quality of voltage at its load-side terminals when the voltage at its source-side terminals is disturbed. A DVR is a waveform synthesis device based on power electronics techniques that is series-connected between the source and the load via an injection transformer. DVR is a customized power device that can be designed for different cases and ratings according to the application and the load requirements. It can also be used in the distribution line feeder to compensate for voltage disturbance in the distribution line.

In this study, a separately excited DVR based on controlled PV-DC link has been designed to mitigate voltage sag and swell, via a correction ratio of up to ± 30%. This is based on assumption that there is a sufficient and constant DC source in the input of the inverter. Depending on the PI controller, suitable compensating voltage vector via series injection transformer will compensate the ratio of voltage disturbance and the load would not be affected by disturbance at the source.

SYSTEM DESCRIPTION

DVR allocation and power circuit

Figure *1* illustrates the position of DVR between the point of common coupling (PCC) and sensitive load. Also, it indicates the main parts of the power circuit of DVR: Voltage Source Inverter (VSI), voltage injection transformer, DC energy storage device and low pass filter.

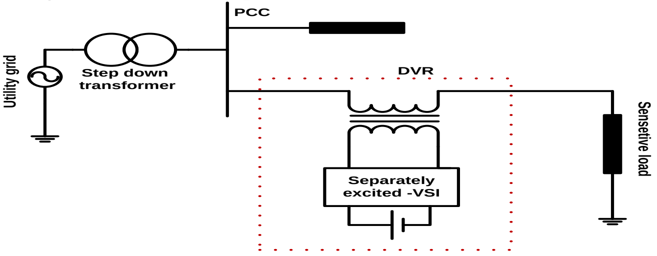

Figure 1 Allocation and power circuit of DVR

The system under analysis is depicted in Figure 2. In this system, the PV generation unit with its controlled DC link voltage is assumed as sufficient DC source to the inverter. The inverter is the main core of this system and consists of three arms each one has two IGBT whose middle points are connected to the grid via an injection transformer which transfers the proper voltage vector to add or subtract to the supply voltage. The injection transformer, or "booster" in DVR systems, guarantees a galvanic isolation and filtration for the pulsated inverter output voltage. The injection transformer is a very essential element in DVR as it faces saturation, overrating, overheating

[14]. Transformer design ratings depends on the rating power calculation of the whole system. Passive filter is an essential part in any grid connected inverter. Due to the high order frequency pulse width modulated signals out on the three arms of the inverter, produced harmonics and switching ripples, the grid passive filters are used to prevent the high order harmonic. In this study, L-filter is used to reduce the switching effect on compensated signal.

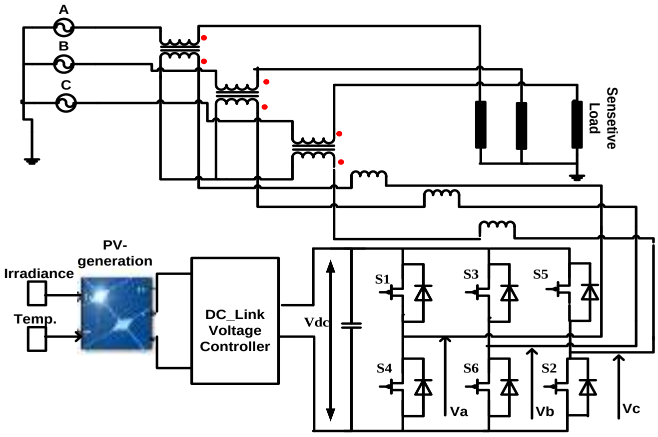

Figure 2 Proposed dynamic voltage restorer

System modelling in the synchronous reference frame

Referring to study [13], DC-AC power converters in grid connected systems are classified into grid-feeding, grid-forming, and grid-supporting power converters. Based on this classification, VSI in DVR systems is considered as a grid-supporting power converter. A grid supporting converter can be connected in parallel with the grid as a controlled AC current source or in series as a controlled AC voltage source. These converters regulate their output current/voltage to keep the value of the grid frequency and voltage amplitude close. In case of DVR, a grid-supporting converter is represented by an ideal AC voltage source which may have positive or negative magnitude (Va_VSI, Vb_VSI and Vc_VSI) as indicated in Figure 3.

Figure 3 represents the simplified model circuit for the proposed system where, V_PCC are terminal voltages of point of common coupling. DVR is represented by three element equivalent series inductances, resistance (Xeq) & (Req) and ideal voltage AC source. The equivalent series inductances mainly represent the equivalent reactive elements in the injection transformer and filter inductance, while the equivalent resistance represent the losses in the DVR.

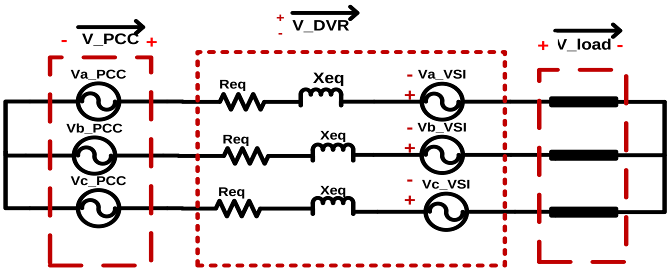

Figure 3 simplified circuit model for the proposed system

Considering that that the primary side of the injection transformer is the inverter side and the secondary side is the grid side, the transformer equivalent circuit element calculated by referring to the primary side of the transformer. Also, In order to decrease the power rating of the inverter switching devices and decrease the voltage drop caused by the DVR, the transformer is designed as a step down transformer with turn's ratio 3:1.

Actually, AC doesn't have "polarity" in the same sense that DC does, but "+" and "-" marks are essential to knowing how to reference the given phase angles of the voltages. AC voltages may aid or oppose to any degree depending on the phase shift between them.

By applying Kirchhoff's voltage law to the circuit in Figure 3, the equation becomes:

$$\overrightarrow{V_{pcc}} = \overrightarrow{V_{load}} \pm \overrightarrow{V_{DVR}} \quad (1)$$

$$\begin{pmatrix} Vl\_a \\ Vl\_b \\ Vl\_c \end{pmatrix} = \begin{pmatrix} Va\_pcc \\ Vb\_pcc \\ Vc\_pcc \end{pmatrix} - \begin{pmatrix} I_{l_a} \\ I_{l_b} \\ I_{l_c} \end{pmatrix} \left((Req) + j(Xeq)\right) \pm \begin{pmatrix} Va_{VSI} \\ Vb_{VSI} \\ Vc_{VSI} \end{pmatrix} \quad (2)$$

Where

V_{pcc}	Terminal voltage at point of common coupling
V_{DVR}	DVR voltage vector
V_{load}	Rated load voltage
V_{l_a}, V_{l_b}, V_{l_c}	Three phase load voltage
V_{a_pcc}, V_{b_pcc}, V_{c_pcc}	Three phase PCC voltage
I_{la}, I_{lb}, I_{lc}	Three phase rated load current
Req+jXeq	DVR equivalent impedance
Va_{VSI}, Vb_{VSI}, Vb_{VSI},	Three phase VSI terminal voltage

From equation (1) it is cleared that the load voltage is dependent on the voltage source (Vpcc) and the controlled DVR voltage. Equation (2) indicates that the compensation process includes the compensation of the voltage drop of DVR itself ($\begin{pmatrix} I_{l_a} \\ I_{l_b} \\ I_{l_c} \end{pmatrix}$ $((Req) + j(Xeq))$ and the controlled VSI which means that if the voltage of common coupling (voltage source) changes, it can be compensated by the DVR.

SYSTEM CONTROL STRATEGY

The control calculations depend on synchronous reference frame theory. Clark transformation equation (3) is used to transform three phase stationary reference frame quantities (abc) to two-phase stationary frame (αβ). Then, the rotating reference frame (Park transformation) is applied to transform a quantity from the stationary frame (αβ) to the rotating frame (dq) equation (4) ,

$$\begin{bmatrix} v\alpha \\ v\beta \\ vo \end{bmatrix} = C \begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{4}$$

Where:

$C = \frac{2}{3}$ for constant voltage and current transformation,

$C = \sqrt{\frac{2}{3}}$ for constant power transformation, and

(θ) is the transformation angle representing the vector position.

The control strategies of interconnection to the power grid are heavily based on the fast and correct detection of the power grid angle (grid synchronization). Phase lock loop (PLL) is an algorithm which is used to make a signal to track another one. It is used to keep the output signal synchronized with the input signal in phase and frequency. This study is based on the stationary reference frame Phase Locked Loop (αβPLL) [15]-[17]. αβPLL closed loop controller is implemented on matlab Simulink.

The proper operation of the inverter and its control method is the core of this system, as the verification for the solution and calculation out from the proposed controller for a large proportion depends on it. In this study, the control of the inverter depends on the space vector pulse width modulation method (SVPWM) which is implemented in matlab /Simulink platform. The linear operation of the SVPWM has a maximum value limited by the voltage of the DC link (Vdc). As a result, it is only possible to get voltages inside a circle of a maximum radius of (Vdc/√3) [18]-[19]. The success of the control system is based on the detection of sag /swell occurrence and the calculation of reference vector voltage sent to the SVPWM as shown in Figure 4.

Figure 4 indicates the block diagram of the control algorithm. Firstly, the continuous detection of the voltage source value (Vpcc) is measured in stationary three phase frame, then converted to (αβ) frame to detect the grid angle (θ) through (Alpha Beta) PLL, and is finally transformed to dq frame for the proposed closed loop PI controller. When voltage sag or swell occurrs, the calculated compensation voltage is needed to feed forward to the closed loop control .On the other hand, the PI controller is worked to reduce the error between the actual and reference load rate voltages.

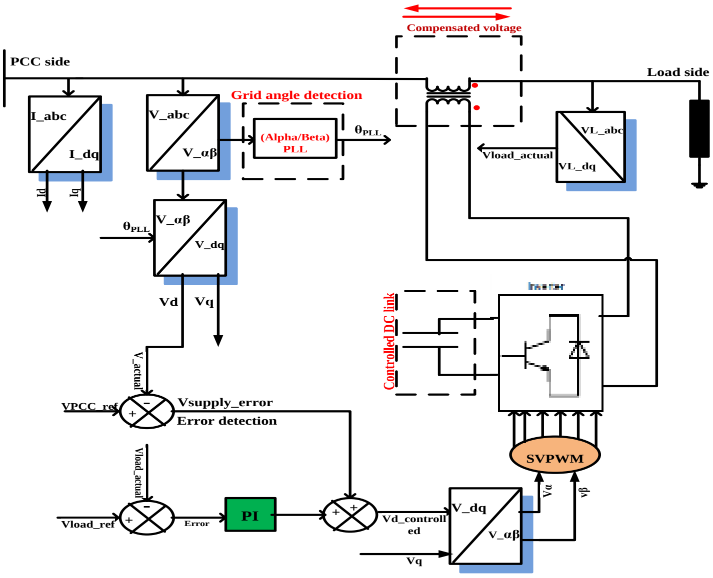

Figure 4 block diagram of proposed control algorithm.

SIMULATION RESULTS

A three phase DVR closed loop control algorithm based on synchronous reference frame theory is designed and simulated using Matlab/Simulink. The conditions of operation are mentioned in appendix1. Applying disturbance at the PCC voltage (sag with ratio -30%) from time = 0.4sec to time= 0.6sec resulted in a changed from 380volt to 231volt (RMS line value), and at time=1sec disturbance (swell with ratio +30%) resulted in a change from 380volt to 429volt (RMS line value).

Figure 5 shows sinusoidal three phase voltage at three points at point of common coupling (Vgrid_line), at DVR (Vdvr_line) and at the load (Vload_line).

Figure 6 and Figure 7 indicate the zoomed view for the previous figure, Figure 5 at the time of sag and swell occurrence, respectively. The figures indicate that the compensation action via DVR insulates the load from voltage sag and voltage swell perfectly.

Figure 8 shows the RMS line value which indicates the injection of DVR during sag and swell which keeps the rated voltage at 380volt.

Figure 9 shows the controller action during disturbance dq component and αβ signals in which the dq component represents the calculated compensation voltage value which transforms to αβ (reference vector value) as input to the SVPWM. It is clear that the calculated Vd component in case sag is +ve value while in swell condition it is –ve value. This direction indicates the series compensation polarity and phase position of the voltage vector compensation direction to be added to or subtracted from the voltage source. The vector reversal is indicated more in zoom view for αβ components in Figure 10.

Figure 11 indicates the injection of active and reactive power during sag and of active and reactive absorption during swell.

Figure 12 provides the system transient response as the DVR had the ability to compensate disturbance within one cycle. The zoomed view indicates that the RMS voltage from the sag starts at t=0.2sec and that the DVR compensated voltage reaches steady state at t=0.22sec. It is clear that the controller is capable of coping with disturbance which occurs at the source side in excellent manner.

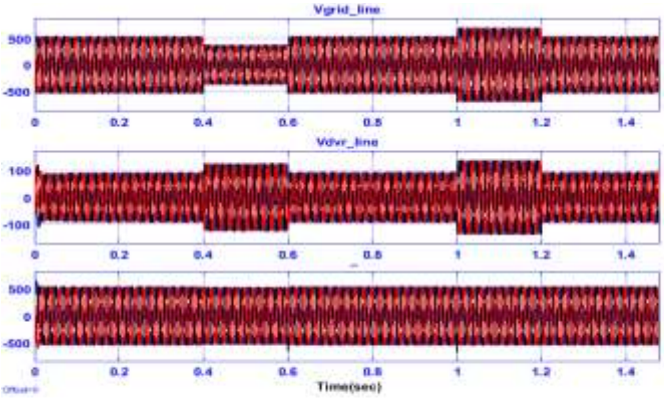

Figure 5 three phase sinusoidal voltages during sag and swell

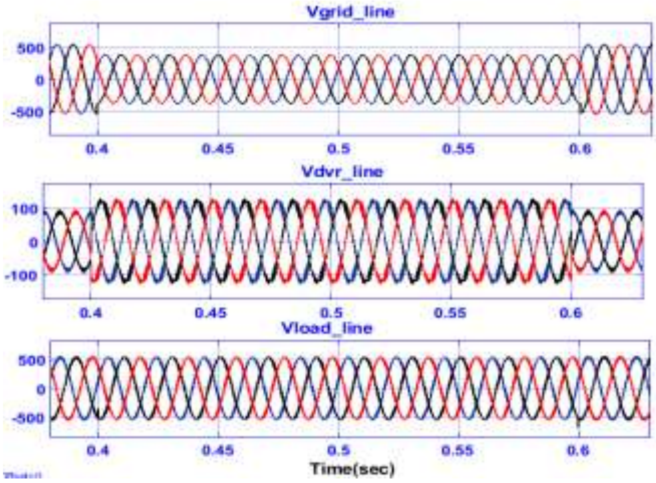

Figure 6 zoom view for sag occurrence

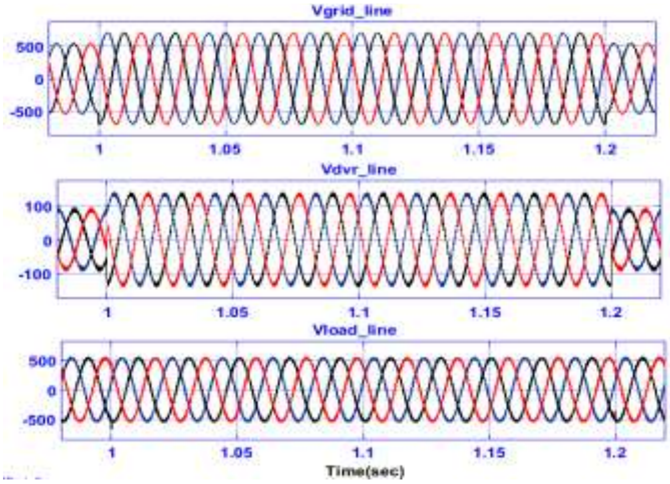

Figure 7 zoom view for swell occurrence

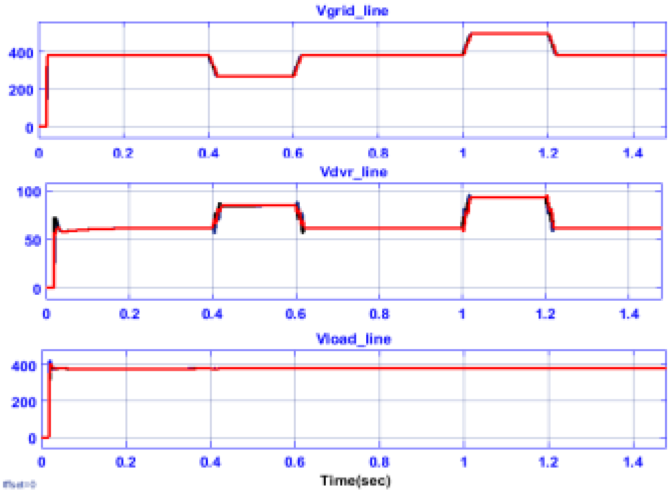

Figure 8 RMS value for voltage during sag and swell

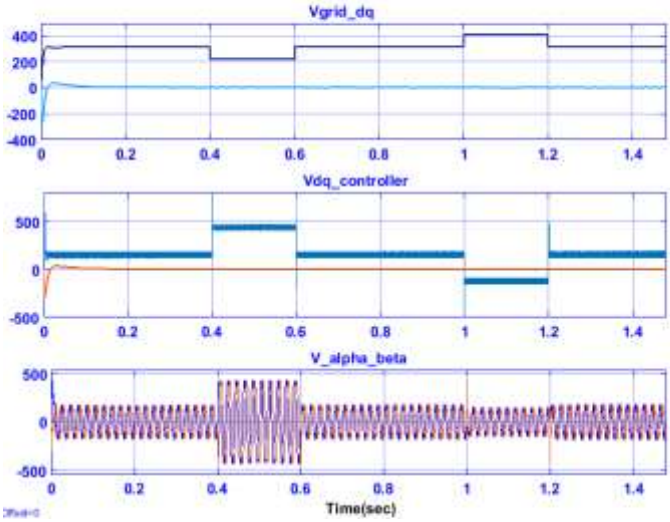

Figure 9 voltage controller action during sag and swell

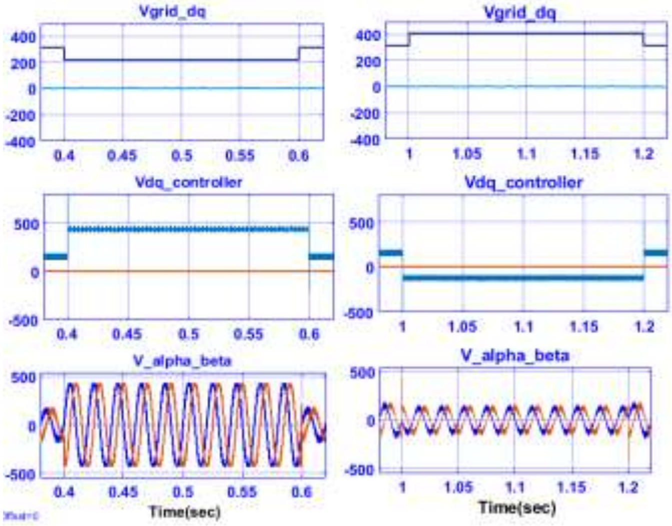

Figure 10 zoom view for the controller action

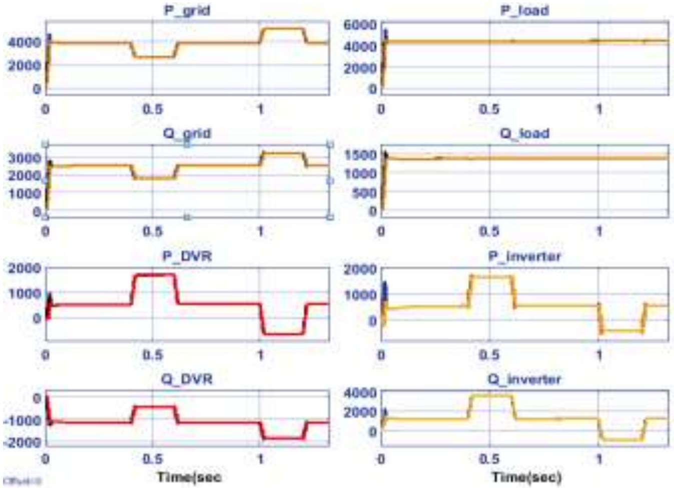

Figure 11 active and reactive power in the proposed system

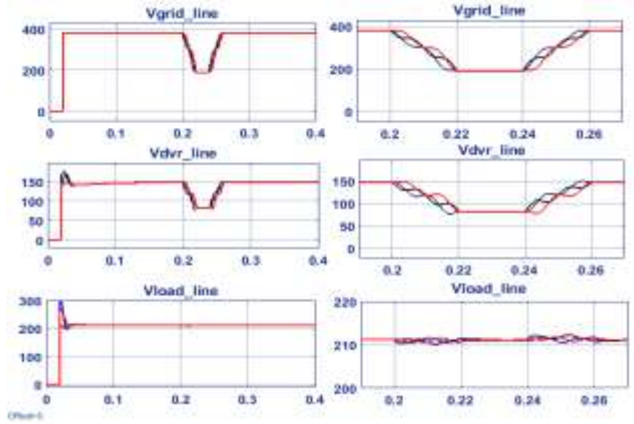

Figure 12 Zoom view for sag and swell compensation within one cycle

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APPENDIX 1

System parameter per phase

Fs(switching frequency	5KHz
R(load)	10 Ω
L(load)	10mH
Load power rating	4620VA
Transformer rated power	3KVA
Inverter rated power	2.5kva
L(filter)	100mH
Transformer turns ratio	3:1
Vprimary(inverter side)	350V
Vsecondary(source side)	117V
Vdc	750V
V_PCC(RMS line value)	381V