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Enhancing Microgrid Power Quality with Dual Output Four-Leg Inverter Topology

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Abstract: *This paper presents the design of a four-leg dual output inverter that aims to compensate voltage and power imbalances between a weak utility and a microsource. The inverter offers several advantages, including component-saving topology and improved reactive power support for the system. The inverter operates in equal frequency mode, which allows for optimal utilization of maximum DC bus voltage and minimizes device ratings. It retains the essential features of a conventional system, such as the ability to compensate for unstable or sagged utility voltage and supply three-phase unbalanced loads with balanced and constant voltage. A carrier-based modulation scheme is employed in this system, and the paper includes a detailed study on the maximum achievable modulation index under various working conditions. The results show that the proposed inverter, when combined with the designed control scheme, significantly enhances power quality, serving as an effective and cost-efficient power conditioner using semiconductor devices. The paper concludes by discussing the system control and the design of its controller. The proposed system's operation is validated through MATLAB simulation, providing further evidence of its effectiveness.*

Keywords: Distributed generation (DG), dual-output four leg inverter, carrier-based pulse width modulation, microgrid, power conditioner, power quality

I. INTRODUCTION

Distributed generation (DG) consists of a wide range of prime mover technologies, viz., internal combustion engines (IC), micro turbines, gas turbines, photovoltaic cell, fuel cells and wind power. Insertion of distributed generation across India is yet to reach significant levels. However, the situation is changing quickly and requires attention to issues related to high insertion of distributed generation within the distribution system. A better way to inspect the potential of distributed generation is to take a system approach which observes generation and associated loads as a "microgrid" or a subsystem

The microgrid concept is a further approach for enabling integration of, in principle, an unlimited quantity of distributed energy resources into the electricity grid. The concept of microgrid is driven by two fundamental principles:

1) A systems perspective is necessary for utilities, customers, and society to capture the full advantages of integrating distributed energy resources into an energy system;

2) The business case is necessary for accelerating adoption of these advanced concepts will be driven, primarily, by lowering the initial cost and enhancing the value of microgrids.

As the generated power produced by these sources is either dc or variable frequency ac, power conversion plays an important role in DG systems [1]–[4], entailing wide application of power electronics in this area [5].

This inverter has two modes of operation and it serves two applications:

Can be used in inverter or ac/ac converter applications

Can be used for power quality conditioner in microgrid system.

This dual-output four-leg inverter is used in a microgrid to control the transmitted power between a microsource and a weak utility while conditioning the power supplied to the microgrid.

The inverter is capable of producing two sets of three phase voltages for supplying balanced or unbalanced three-phase loads. It can also supply two triple sets of single-phase loads, each set of its own frequency and each voltage of its own amplitude.

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The given inverter operates in equal frequency (EF) mode and different frequency (DF) mode of operation. In equal frequency (EF) mode voltage amplitudes are independent whereas their frequencies are equal. In different frequency (DF) mode of operation the output voltages are fully independent in terms of amplitudes and frequencies. There are many advantages of EF mode over DF mode: the maximized voltage utilization and minimized converter power loss [6].

Since in this application the converter is functioning in EF mode, therefore it has advantages of high dc bus voltage utilization, lower device ratings, and less dissipated switching power [6]. This inverter also reduces use of two separate four-leg converters, use of two separate four-leg converters may result in a complex system using two dissimilar power converters and a large number of power switches. The proposed system retains all the desirable characteristics of the conventional one. Also, it replaces the two dissimilar converters with one integrated structure which uses less number of switches and reduces the system complexity and cost

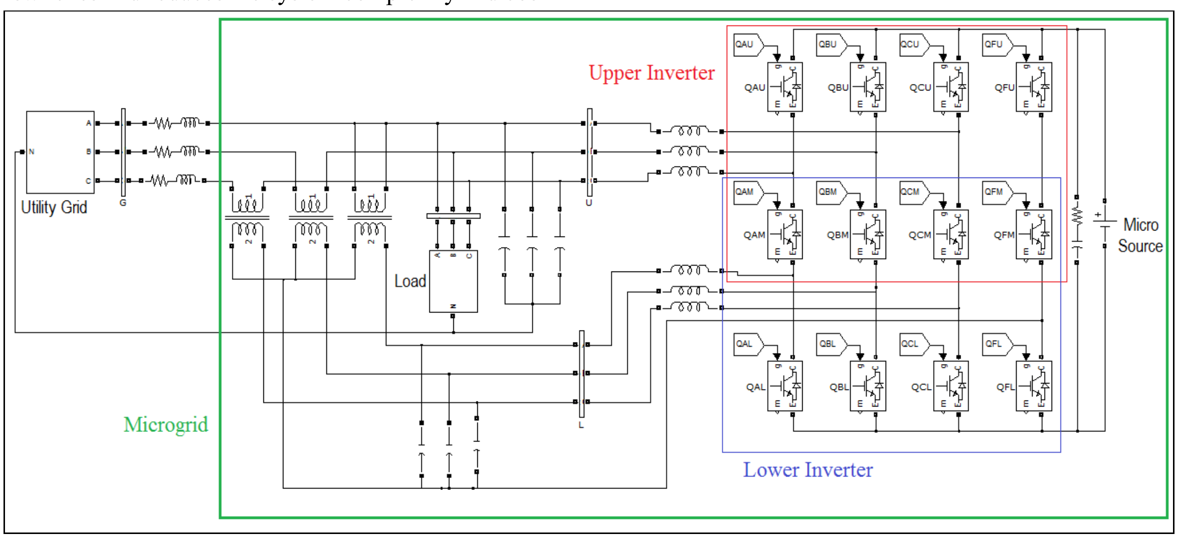

Figure 1 Dual-Output Four-Leg Inverter used in the microgrid

II. DUAL-OUTPUT FOUR-LEG INVERTER

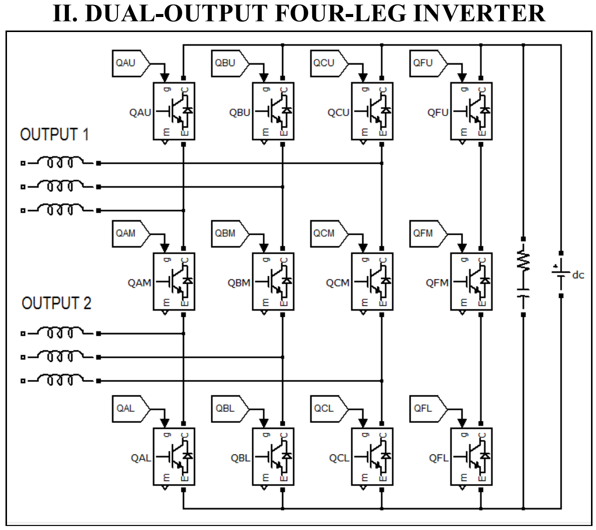

Figure 2 Dual-Output Four-Leg Inverter

This inverter operates with two modes of operation: Different Frequency mode in which output frequencies can be different from each other and Equal Frequency mode in which output frequencies should be equal. The carrier-based pulse width modulation scheme of the dual output converter is developed and explained in [7]. The converter operates in equal frequency mode (EF mode). Owing to which system becomes advantageous with dc bus voltage utilization becomes higher, device ratings become lower and it dissipates less switching power.

First two offset voltages are calculated by using phase voltage commands of the two outputs as the fourth leg modulation signals shown in (1):

$V_{fnj} = (-V_{max\,j}/2)\ V_{min\,j} > 0,$

$V_{fnj} = (-V_{min\,j} / 2)\ V_{max\,j} > 0,$

$V_{fnj} = -(V_{max\,j} + V_{mim\,j}) / 2,$ otherwise (1)

Where, j = U or L, V_{max} and V_{min} are the instant maximum & minimum values of each of the upper & lower output phase voltages.

The next step would be finding the pole voltage commands ($V_{in,\ i=(a,\ b\ \&\ c)}$) by adding the acquired offsets to the phase voltage commands

$V^*_{an\,j} = V^*_{af\,j} + V_{fn\,j}$

$V^*_{bn\,j} = V^*_{bf\,j} + V_{fn\,j}$

$V^*_{cn\,j} = V^*_{cf\,j} + V_{fn\,j}$ (2)

Where, j = U or L

The pole voltage commands will work as the modulation signals of the remaining three legs. Now, offsets should be added to each of these sets therefore the upper and lower output modulation signals are shifted up and down respectively by doing this we can avoid their interference. According to the inverter operation mode, these offsets are determined; equation (3) is used for EF mode:

$Offset_U = 1 - M_U$

$Offset_L = M_L - 1$ (3)

Where, j = U or L

The use of DF operation gives outputs of limited indices for two outputs. Which has many disadvantages like in reduced dc bus voltage utilization and this reduced dc bus voltage utilization gives increased dc bus voltage level. Inversely, in EF mode, the phase difference between the output voltages, is the only factor, that restricts the modulation indices. Equation (4) computes this limitation and illustrates the principal condition that should be maintained during the converter operation in EF modes:

$M_L \sin(\omega_L t + \alpha_L) + V_{fn\,L} + Offset_L$

$\leq M_U \sin(\omega_U t + \alpha_U) + V_{fn\,U} + Offset_U$ (4)

The inclusion of an additional neutral leg in a three-phase four-leg inverter enables it to effectively handle load unbalance in a standalone power supply system. The primary objective of this inverter is to preserve the desired sinusoidal output voltage waveform, regardless of the overall loading conditions and transients. The scenario assumes that a non-linear and unbalanced load is connected to three-phase balanced source voltages. The four-leg inverter compensates for the load unbalance by dynamically adjusting the output voltages to maintain a sinusoidal waveform. This capability is crucial for ensuring stable and reliable operation of the power supply system. By incorporating the additional neutral leg, the three-phase four-leg inverter provides a robust solution for maintaining voltage balance and waveform quality, even in the presence of non-linear and unbalanced loads.

Lower output voltage reference = (Undistorted utility voltage $V_{G,\ Normal}$) – (Distorted measured utility voltage V_G)

$V_{G\,(Ref)} = V_{G,\ Normal} - V_{G,\ Actual}$

III. DUAL-OUTPUT FOUR-LEG INVERTER USED IN THE MICROGRID

The system of Dual-Output Four-Leg Inverter used in the microgrid is displayed in figure 1. The use of dual-output four-leg inverter reduces use of two separate inverters. Henceforth, in addition to reducing the number of semiconductor switches, gate drive and control circuits, and consequently cost, it give an integrated structure and removes the need for two inverters of different ratings. The diagram shows two sources one is utility and other is microsource. Microsource consisted of various renewable sources like solar plant, small wind plant, small hydro and non-renewable like small diesel power station etc. In normal condition, the load is supplied both by the utility and the microsource. The inverter lower output is connected in series with the microgrid, and inverter upper output is connected to the microsource and microgrid. The upper output converts the microsource dc voltage to constant and balanced three-

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phase voltages irrespective of the utility conditions. The lower output however acts in communication with the utility as a compensator and power quality conditioner to reduce/remove its sag and unbalance, and to reduce occurrence of island operation. All above problems avoided by restricting the flowing current between grid and microgrid during fault. This objective is achieved by injecting voltage through series transformers.

Under fault conditions, the series converter does not contribute to supplying power to the microgrid loads. Instead, it focuses on generating reactive power to compensate for the utility voltage sag. The reduced power from the utility is entirely provided by the microsource through the parallel converter. To achieve this, a flux control algorithm is employed, allowing the series converter to act as a variable inductor to limit the fault current without generating active power.

However, in this report, the lower output, which is connected in series with the utility, not only restricts the fault current but also transfers a portion of active power from the microsource to the load. Essentially, during a fault, both outputs supply active power along with reactive power to the microgrid loads. By minimizing the phase difference between the output references of both converters when they are active, the modulation index limitation is reduced. This strategy prevents island operation, allows utilization of grid power at a reduced rate, and ensures that active power is shared between both outputs during fault conditions.

Since the lower output reference is defined as the difference between ideal undistorted utility voltage $V_{G,\ NORMAL}$ and measured utility voltage V_G, upper and lower output voltages have equal frequencies, and hence, the EF mode is suitable for this application. The only limiting factor in modulation indices in EF mode is the phase difference between the output voltages and hence their references. Due to the important consequence of this limitation which is reduced dc bus utilization, i.e., increased dc bus voltage level, next section is designated for investigation of this issue and its influence on the converter performance. It will be demonstrated that under most common fault conditions, the limitation of the converter modulation indices for both outputs is confined in an acceptable range imposing the least negative effects on the system operation.

IV. OUTPUT CONTROLLER DESIGN

Proportional Resonant (PR) controller The Laplace transform of the ideal PR controller is:

$C(S) = K_P + (2\ (K_R).s\ /\ (S^2 + \omega^2))$ (5)

Where K_P the proportional is gain and ω, K_R are the resonant frequency and gain, respectively

The PI controller provides an infinite gain with a constant variable; it get a quick response to a step reference without steady-state error, but is unable to track a sinusoidal reference. On the contrary, the PR controller provides an infinite gain at the selected frequency (resonant frequency) and zero phase-shift.

To generate the required set of three-phase voltages based on their references, a simple dual-loop control algorithm is used. This algorithm consists of an outer voltage control loop and an inner current control loop. The outer voltage control loop is responsible for regulating the output voltage of the inverters to match the desired reference voltages. It continuously monitors the output voltage and compares it to the reference voltage. Any deviation is corrected by adjusting the control signals of the inverters. The inner current control loop operates within each inverter and ensures that the current flowing through the inverters matches the desired reference current. This control loop measures the output current and compares it to the reference current. Any difference is adjusted by manipulating the control signals within the inverters.

By combining the outer voltage control loop and the inner current control loop, the inverters are able to generate the required three-phase voltages accurately and maintain them in accordance with their respective references.. Figure 3 displays the control block diagram of all inverter phase and leg. $G_V(S)$ and $G_i(S)$ are, respectively, voltage and current controllers and M is the modulation index. Passing through $G_V(S)$ in the voltage control loop, the reference current is derived from the error of the output voltage. [8]

To design current and voltage controllers, the system transfer functions, $G_V(S)$ and $G_i(S)$ respectively, for voltage and current loops, are obtained in (6) & (7)

$G_V(S) = [(L_L S + R_L) / (R_L C_f S + 1)]$ (6)

$G_i(S) = x / y$ (7)

Where,

$x = [(V_{DC} / 2)\ (L_L C_f\ S^2) + (R_L C_f S + 1)]$

$y = [(L_L L_f C_f\ S^3) + (R_L L_f C_f\ S^2 + (L_L + L_f)S + R_L]$

Tuning the PR controller, desirable phase margin and gain margin can be achieved and the steady-state error can be prevented. Table 1 lists the PR gains of the upper and lower output controllers which are equal for the three phases.

Table 1 Gains of the PR Controller

	Upper Output		Lower Output	
Gain	K_P	K_R	K_P	K_R
Current Control Loop	0.05	5	0.05	5
Voltage Control Loop	0.08	20	0.8	50

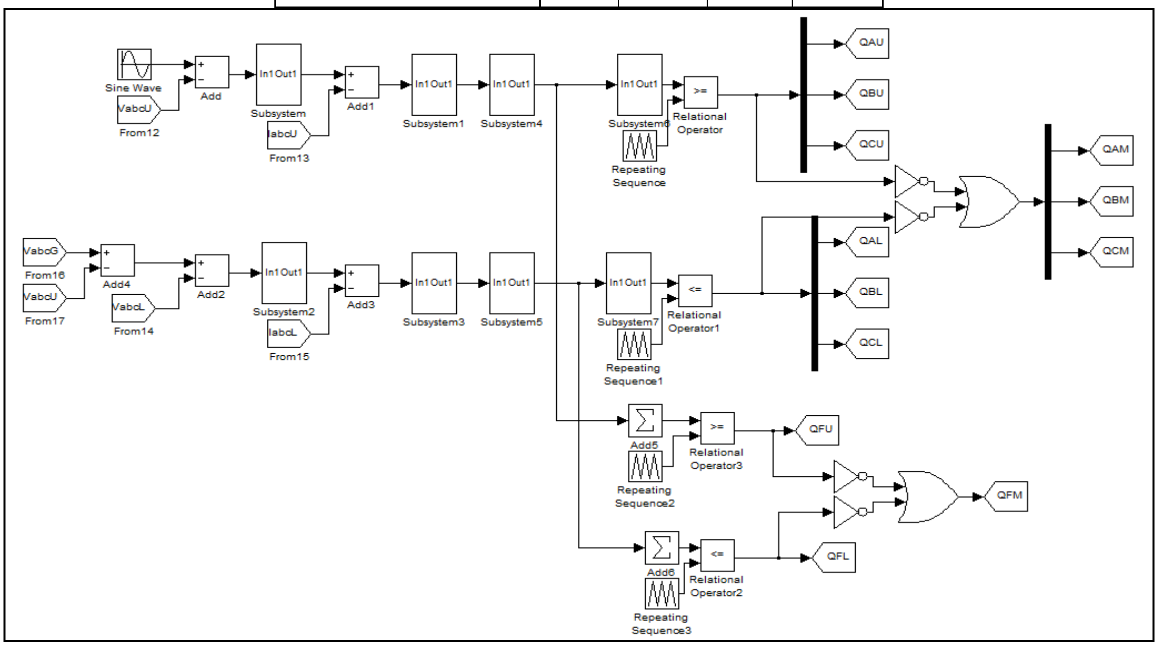

Figure 3 control block diagram of all inverter phases and legs

V. SIMULATION RESULTS

To examine the performance of the suggested system, MATLAB simulation is carried out for two modes. In the first mode, the lower output is inactive and no compensation is done by lower output. Therefore, occurrence of fault would result in uncontrollable line current which would activate protection devices and initiate island operation leading to termination of power transfer between the utility and the microgrid. This is for providing the ground for comparison with the second mode in which the lower output will be active and the system works in its full capacity.

Parameters of System under performance:

The details of the system under simulation is as follows:

Utility Voltage: 170-V (Prior fault) and Frequency: 50-Hz

Transmission Line parameters (Phase a, b & c):

R = 0.1Ω, L = 1mH

DC source voltage: 400-V

Upper and Lower inverter LC filter: L = 1mH (in line),

C = 1μF (shunt with line: Y connection)

Series transformer: Nominal power = 10kVA, Frequency: 50-Hz, VRMS = 170-V, R = 0.002Ω, L = 0.08H, Magnetization Resistance & Inductance are 500Ω and 500H respectively.

The unbalanced load supplied by the microsource through the upper output:

Table 2 Unbalanced load parameters

	Phase a	Phase b	Phase c
R_L (Ω)	15	20	12
L_L (mH)	25	15	20
V_G (V)	110∟0	100∟-90	120∟90

IGBT internal resistance, R = 10-3Ω , IGBT snubber resistance, R = 105Ω, switching frequency of IGBT 10kHz
Fault occurs at time t = 0.4s

Effect on Voltage & Current:
Figure 4 displays the utility voltage which experiences severe sag and unbalance from t = 0.4s ON. Due to fault, and lack of control and compensation in the first mode, an unwanted current has flowed between the microgrid and the grid as shown in figure 5.
The system behaviour when the series compensator is active is displayed in figure 6 to 9. It is shown that when the compensator is active, the upper output voltage [Figure 6] and current [Figure 7] are not affected by the utility fault at all. Furthermore, the fault current is restricted [Figure 8] compared to previous mode via the voltage injected by the lower output [Figure 9].

Table 3 Comparison of system performance

Conditions	Pre-fault		Post-fault	
	Grid Voltage (V)	Line Current (A)	Grid Voltage (V)	Line Current (A)
No compensation (i.e. lower inverter output is inactive)	170	5	110 - 130	5 - 20
With compensation (i.e. lower inverter output is active)	-	-	170	5

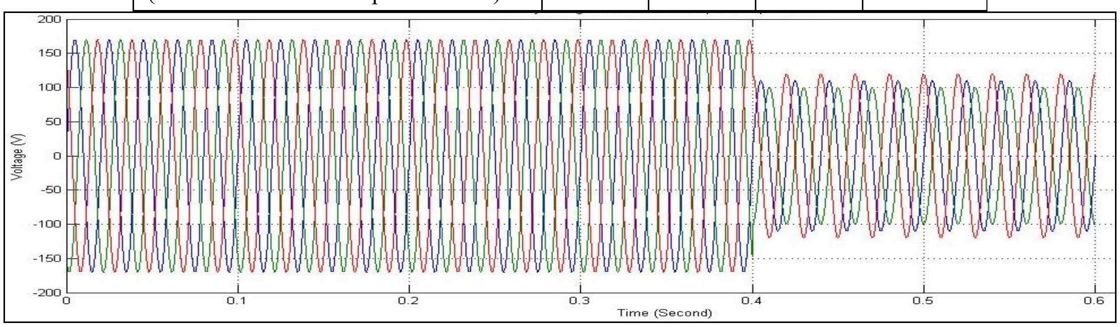

Figure 4 Utility voltage without lower compensation

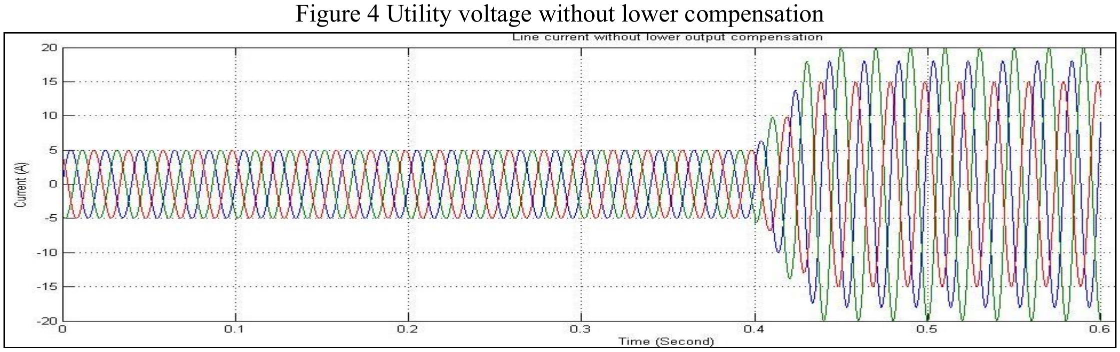

Figure 5 Line current without lower output compensation

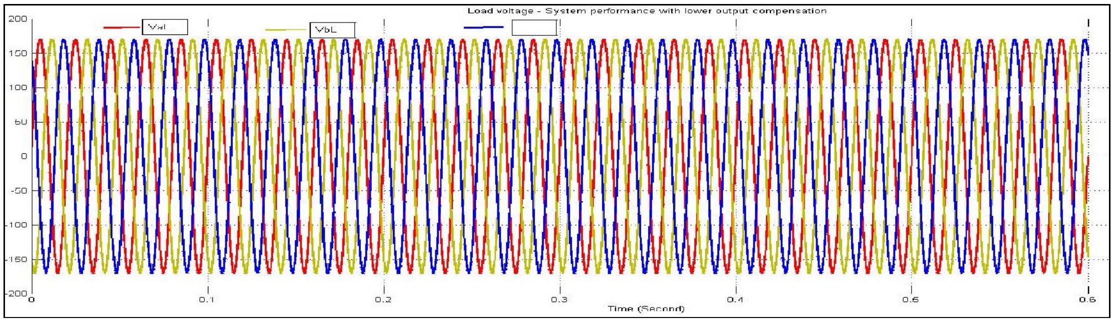

Figure 6 System performance with lower output compensation

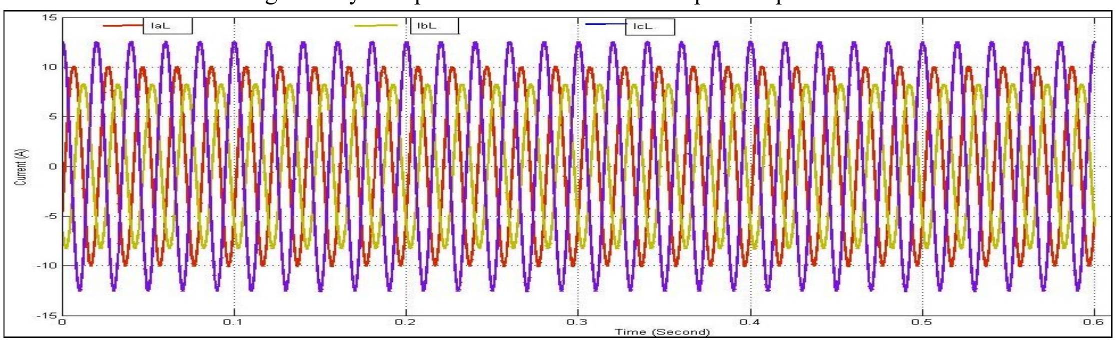

Figure 7 Load Voltage with lower output compensation

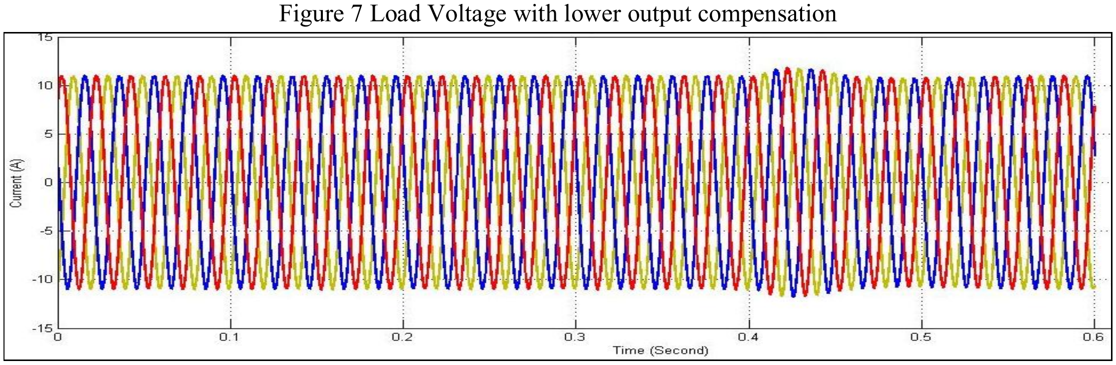

Figure 8 Line Current with lower output compensation

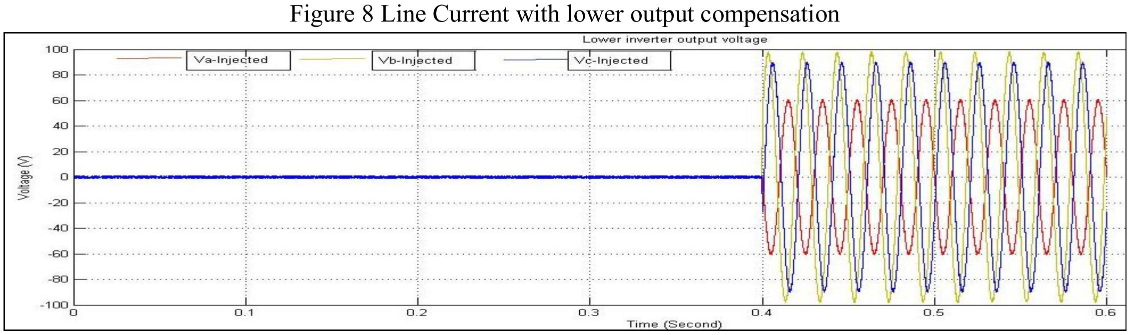

Figure 9 Lower output voltage with lower output compensation

VI. CONCLUSION

The used dual-output four-leg inverter unites all the attractive features of the converter into power enhancement of a Distributed Generation system. In this application, Equal Frequency mode of operation of the inverter was employed in which the dc bus voltage utilization is maximized, and the bus voltage level and voltage stress of the power switches are comparable to the conventional topology. Also, the used system reduces the conventional system problem and cost is decreased by reducing the number of required power switches and it also replaces two converters into one unified inverter to do same task. The simulation results confirmed the effective performance of the proposed configuration in enhancing the power quality and reliability of the microgrid in which it was implemented. Using the proposed system, the necessity of adapting island operation would be minimized, and all the complications of resynchronization of utility and microgrid for reconnecting them at the end of island operation, in essence, after the fault is removed, are avoided.

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