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Stability Analysis of Distributed Generation System for Three Phase Inverter Interfacing with Ultracapacitor

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Abstract:
Now a days the use of the renewable energy systems has been increased in the distributed generation. This paper presents an Adaptive voltage control theory for the three phase system, which is feeded by solar PV system (renewable energy system). An ultra-capacitor is interfaced for the proposed system through a DC-DC converter. With this interface, the disturbances in the DC output of the PV panels will be reduced and the DC input to the three phase inverter system will maintain constant. The DC-DC converter will regulates the DC voltage of the ultra- capacitor. Ultra-capacitors are used to improve the system's reliability and energy conversion efficiency. The proposed adaptive voltage control technique is a closed loop control system, which combines an adaption control term and a state feedback control term. This proposed control strategy has exceptional voltage regulation performance under various types of loads. The MATLAB/Simulink software is used to test the simulation results under the parameter uncertainties and is compared to the performances of the corresponding non-adaptive voltage controller. These results show that a good DC bus voltage regulation in the tested conditions.

Index Terms: Adaptive Voltage Control, Distributed Generation System (DGS), Stability Analysis, Standalone Operation, Uncertainties, Voltage Source Inverter.

I. INTRODUCTION

In recent years, eco-friendly distributed generation systems (DGS) such as wind turbines, solar cells, and fuel cells are dramatically growing because they can fulfill the increasing demand of electric power due to the rapid growth of the economy and strict environmental regulations regarding greenhouse gas emissions. Generally, the DGSs are interconnected in parallel with the electric utility grid and provide maximum electric power to the grid. However, there are some areas where the connection to the grid is expensive or impractical and then small scaled standalone DGSs are the only efficient and economical options. In such DGSs, depending on consumers' power demand, there are situations where some DGSs operate in parallel or independently. In either case, a stable operation of each DGS unit is as important as the stability of the parallel operating DGSs in which the proper load sharing of each unit is one of main research issues since the voltage controller is commonly used in a single DGS unit or multiple DGS units. For this reason, the voltage controller design for a single DGS unit, which can guarantee a good voltage regulation under unbalanced and nonlinear loads, is an interesting topic in the field of the DGSs control. The continual rise in electricity demand, combined with serious environmental problems created by traditional energy systems have been driving societies towards the use of renewable energy sources. Besides being environmentally friendly, renewable energy sources are continually renewed by the cycle of nature and are considered to be practically inexhaustible. As a result, the future of these sources as a typical alternative for the traditional sources looks very bright. However, the natural variability of some renewable sources due to their strong dependence on the weather conditions result to a high fluctuated output power, which impacts on the local loads that are sensitive to pulsating power. Moreover, the renewable sources generated power does not always match the demanded load power. Hence, there is a need to support these sources by use of energy storage device, where it either injects its stored energy or absorbs the excess energy during the transients in the renewable source; resulting in a smooth output power to the load. Amongst storage devices, ultra-capacitor is preferred due to its long life-time, good electrical behavior and to its relatively low initial cost in comparison with modern batteries. In addition, it is positively characterized by its high power density, low losses while charging and discharging, and it's very low equivalent series resistor (ESR) which allows it to deliver and absorb very high currents and to be charged very quickly. Furthermore, ultra- capacitor can provide large transient power instantly. Consequently, the use of ultra-capacitor as a storage element increases the effectiveness of the renewable energy source utilization and also improves the capability of dealing with steady-state and transient dynamics. Connecting the renewable source and the ultra- capacitor requires a power converter and a DC link. The converter must have the capability to allow both directions of power flow between the ultra-capacitor and the DC link, and also the ability to increase or decrease the voltage level in each power flow direction; since the voltage level of the ultra-capacitor and the DC link are different. Therefore, a bidirectional DC-DC converter is used. In bidirectional DC- DC converters, there are two modes of operation. The first mode is the boost mode, where the ultra-capacitor is discharged to a higher voltage level at the DC link; in the second mode, namely the buck mode; here the excess power from the renewable source charges ultra-capacitor. This paper proposes a robust adaptive voltage controller of the three-phase voltage source inverter for a standalone DGS with various types of loads. First, the state-space model of the three-phase inverter is derived, which considers the uncertainties of system parameters. The proposed adaptive control technique combines an adaption control part and a state feedback control part. The adaption control part compensates for system uncertainties, whereas the state feedback control part forces the error dynamics to converge exponentially to zero. The proposed control strategy is not only simple, but also insensitive to system uncertainties and sudden load disturbances. It should be noted that almost all published papers do not study the effects of the uncertainties in the system parameters. Moreover, it is proven that the proposed closed-loop control system is globally stable. The proposed adaptive controller ensures outstanding voltage control performance under various types of loads. These features can overcome the drawbacks of previously published papers.

II. SYSTEM MODEL

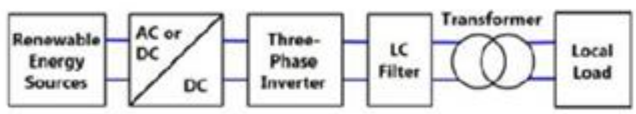


Figure.1. Block diagram of a standalone DGS using renewable energy sources

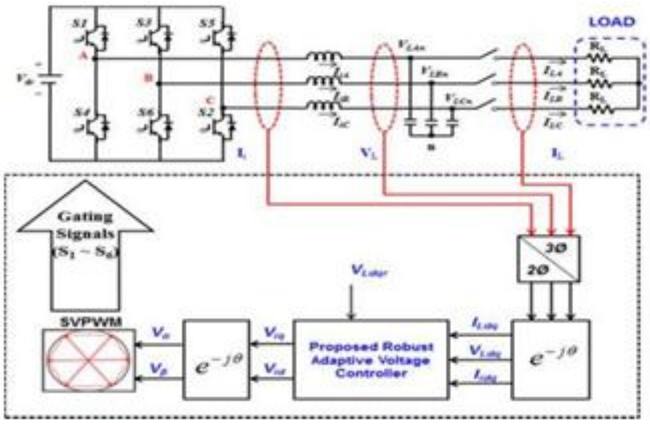


Figure.2. Schematic diagram of a three-phase dc to ac inverte

Fig. 2 shows a schematic diagram of a three-phase dc–ac inverter in a standalone application. In this figure, it consists of a dc voltage source (*V*dc), a three-phase inverter (*S*1 to *S*6), an output filter (*Lf* and *Cf*), and a three-phase resistive load (*RL*). The *LC* output filter is an indispensable part in this circuit because it plays a role in eliminating harmonic components of the inverter output voltage caused by high-frequency switching actions.

The *LC* output filter shown in Fig. 2 yields the following state equations by using *Kirchhoff's voltage law* and *Kirchhoff's current law*:

$$\begin{cases} \frac{d\mathbf{V}_L}{dt} = \frac{1}{C_f}\mathbf{I}_i - \frac{1}{C_f}\mathbf{I}_L \\ \mathbf{T}_i\frac{d\mathbf{I}_i}{dt} = -\frac{1}{L_f}\mathbf{T}_i\mathbf{V}_L + \frac{1}{L_f}\mathbf{V}_i \end{cases} \quad (1)$$

Where

$$\mathbf{T}_i = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

The state equations (1) in the stationary *abc* reference frame can be transformed to the following equations in the synchronously rotating *d–q* reference frame:

$$\begin{cases} \dot{V}_{Ld} = \omega V_{Lq} + k_1 I_{id} - k_1 I_{Ld} \\ \dot{V}_{Lq} = -\omega V_{Ld} + k_1 I_{iq} - k_1 I_{Lq} \\ \dot{I}_{id} = \omega I_{iq} - k_2 V_{Ld} + k_3 V_{id} + k_4 V_{iq} \\ \dot{I}_{iq} = -\omega I_{id} - k_2 V_{Lq} - k_4 V_{id} + k_3 V_{iq} \end{cases} \quad (2)$$

Where ω is the angular frequency ($\omega = 2\pi \cdot f$), f is the fundamental frequency of output voltage or current, and

$$k_1 = \frac{1}{C_f}, \quad k_2 = \frac{1}{L_f}, \quad k_3 = \frac{1}{2L_f}, \quad k_4 = \frac{1}{2\sqrt{3}L_f}.$$

In this work, the following assumptions are used to design an adaptive voltage controller:

1) The desired load *d–q* axis voltages (*VLqr* and *VLdr)* are considered as constant during a small sampling period.
2) The load *d–q* axis currents (*ILd* and *ILq)* vary slowly during a small sampling period.

Denote the reference values (*I∗idr* and *I∗iqr)* of the inverter currents (*Iid* and *Iiq)* in the *d–q* axis as

$$I^*_{idr} = I_{Ld} - \frac{1}{k_1}\omega V_{Lqr}, \quad I^*_{iqr} = I_{Lq} + \frac{1}{k_1}\omega V_{Ldr}. \quad (3)$$

These inverter *d–q* axis current references can be confined within the maximum allowable values as shown

$$I_{id(q)r} = \begin{cases} I^*_{d(q)r} & \text{If } |I^*_{d(q)r}| \le I_{\max} \\ \frac{I^*_{d(q)r}}{|I^*_{d(q)r}|} I_{\max} & \text{If } |I^*_{d(q)r}| > I_{\max} \end{cases} \quad (4)$$

Where *I*max represents the maximum allowable magnitude of the inverter currents. It should be noted that the output filter capacitance *Cf* usually satisfies 0 < *Cf* _ 1, i.e., 1 _ *k*1 < ∞. Thus we may use the assumption 1 _ *k*1 ± | Δ*k*1 | < ∞ leading to the following equations:

$$I_{idr} = I_{Ld} - \frac{1}{k_1}\omega V_{Lqr} \approx I_{Ld} - \frac{1}{k_1 + \Delta k_1}\omega V_{Lqr}$$
$$I_{iqr} = I_{Lq} + \frac{1}{k_1}\omega V_{Ldr} \approx I_{Lq} + \frac{1}{k_1 - \Delta k_1}\omega V_{Ldr} \quad (5)$$

Where Δ*k*1 denotes the imprecision of the parameter *k*1 from (2) and (3), four state variables are defined as follows:

$$x_1 = V_{Ld} - V_{Ldr}, \quad x_2 = V_{Lq} - V_{Lqr}$$
$$x_3 = I_{id} - I_{idr}, \quad x_4 = I_{iq} - I_{iqr}.$$

With this definition, the system model (2) can be rewritten as

$$\begin{cases} \dot{x}_1 = \omega x_2 + k_1 x_3 \\ \dot{x}_2 = -\omega x_1 + k_1 x_4 \\ \dot{x}_3 = \omega I_{iq} - k_2 V_{Ld} + k_3 V_{id} + k_4 V_{iq} \\ \dot{x}_4 = -\omega I_{id} - k_2 V_{Lq} - k_4 V_{id} + k_3 V_{iq} \end{cases} \quad (6)$$

In considering the equation (5) and the uncertainties of system parameters, the model (6) becomes

$$\begin{cases} \dot{x}_1 = \omega x_2 + k_1 x_3 + \Delta k_1 x_3 \\ \dot{x}_2 = -\omega x_1 + k_1 x_4 + \Delta k_1 x_4 \\ \dot{x}_3 = k_3 V_{id} + k_4 V_{iq} + \Delta k_3 V_{id} + \Delta k_4 V_{iq} \\ \qquad - (k_2 + \Delta k_2) V_{Ld} + \omega I_{iq} \\ \dot{x}_4 = -k_4 V_{id} + k_3 V_{iq} - \Delta k_4 V_{id} + \Delta k_3 V_{iq} \\ \qquad - (k_2 + \Delta k_2) V_{Lq} - \omega I_{id} \end{cases} \quad (7)$$

Where Δ*k*1 to Δ*k*4 represent the uncertain components of four parameters (*k*1 to *k*4), respectively.

I. ADAPTIVE VOLTAGE CONTROLLER DESIGN AND STABILITY ANALYSIS: The control inputs *Vid* and *Viq* can be defined as two control components, respectively:

$$V_{id} = V_{id1} + V_{id2}, \quad V_{iq} = V_{iq1} + V_{iq2} \qquad (8)$$

Where *Vid*1 and *Viq*1 are the feedback control components to stabilize the error dynamics of the system, whereas *Vid*2 and *Viq*2 are the nonlinear compensating control components given by

$$\begin{cases} V_{id2} = \dfrac{-k_4\omega I_{id} - k_3\omega I_{iq}}{(k_3^2 + k_4^2)} \\ V_{iq2} = \dfrac{-k_4\omega I_{iq} + k_3\omega I_{id}}{(k_3^2 + k_4^2)} \end{cases} . \qquad (9)$$

Referring to (8) and (9), the system model (7) can be rearranged as the following:

$$\begin{cases} \dot{x}_1 = \omega x_2 + k_1 x_3 + \Delta k_1 x_3 \\ \dot{x}_2 = -\omega x_1 + k_1 x_4 + \Delta k_1 x_4 \\ \dot{x}_3 = k_3 V_{id1} + k_4 V_{iq1} + \Delta k_3 V_{id} + \Delta k_4 V_{iq} - (k_2 + \Delta k_2) V_{Ld} \\ \dot{x}_4 = -k_4 V_{id1} + k_3 V_{iq1} - \Delta k_4 V_{id} + \Delta k_3 V_{iq} - (k_2 + \Delta k_2) V_{Lq} \end{cases} \qquad (10)$$

Or

$$\begin{cases} \dot{x}_1 = \omega x_2 + k_1 x_3 + \Delta k_1 x_3 \\ \dot{x}_2 = -\omega x_1 + k_1 x_4 + \Delta k_1 x_4 \\ \dot{x}_3 = k_3 V_{id1} + k_4 V_{iq1} - k_3 f_1(x,t) - k_4 f_2(x,t) \\ \dot{x}_4 = -k_4 V_{id1} + k_3 V_{iq1} + k_4 f_1(x,t) - k_3 f_2(x,t) \end{cases} \qquad (11)$$

Where

$$f_1(x,t) = a_1 V_{id} + a_2 V_{iq} + a_3 V_{Ld}$$

$$f_2(x,t) = a_4 V_{id} + a_5 V_{iq} + a_6 V_{Lq}$$

in which *a*1, *a*2 , . . ., *a*6 are unknown constants,

$$a_1 = a_5 = -\frac{k_3 \Delta k_3 + k_4 \Delta k_4}{k_3^2 + k_4^2}$$

$$a_2 = -a_4 = \frac{k_4 \Delta k_3 - k_3 \Delta k_4}{k_3^2 + k_4^2}$$

$$a_3 = a_6 = k_2 + \Delta k_2.$$

Thus, the model (11) can be rewritten in the state-space form as

$$\dot{x} = (A + \Delta A)x + B[u - f(x,t)] \qquad (12)$$

$$f(x,t) = [f_1(x,t) \quad f_2(x,t)]^T = W\Pi^*$$

$$A = \begin{bmatrix} 0 & \omega & k_1 & 0 \\ -\omega & 0 & 0 & k_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta A = \begin{bmatrix} 0 & 0 & \Delta k_1 & 0 \\ 0 & 0 & 0 & \Delta k_1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} = EF\Delta k_1$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k_3 & k_4 \\ k_4 & k_3 \end{bmatrix}, E = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$F^T = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, u = \begin{bmatrix} V_{id1} \\ V_{iq1} \end{bmatrix}$$

Where $W = \begin{bmatrix} V_{id} & V_{iq} & V_{Ld} \\ V_{iq} & -V_{id} & V_{Lq} \end{bmatrix}, \Pi^* = [a_1 \quad a_2 \quad a_3]^T$

Assume that there exists a positive definite matrix $P \in R^{4\times4}$ satisfying the following inequality:

$$(A + \Delta A)^T P + P(A + \Delta A) + Q - 2PBR^{-1}B^T P < 0 \qquad (13)$$

Or

$$A^T P + PA - 2PBR^{-1}B^T P + Q + \Delta A^T P + P\Delta A < 0 \qquad (14)$$

Where $Q \in R^{4\times4}$ and $R \in R^{2\times2}$ are positive definite matrices. The above inequality (14) is satisfied if the following inequality holds for some positive ρ:

$$A^T P + PA + Q - 2PBR^{-1}B^T P + \rho PEE^T P + \frac{1}{\rho} F^T F \Delta k_1^2 < 0 \qquad (15)$$

Where the following inequality is used

$$\Delta A^T P + P\Delta A = \Delta k_1 F^T E^T P + \Delta k_1 PEF \le \rho PEE^T P + \frac{1}{\rho} F^T F \Delta k_1^2.$$

Assume that $|\Delta k1| \le \zeta$ for some known positive constant ζ; then inequality (15) is satisfied if the following Riccati-like inequality has a positive definite solution matrix $P \in R^{4\times4}$:

$$A^T P + PA + Q - 2PBR^{-1}B^T P + \rho PEE^T P + \frac{1}{\rho}\zeta^2 F^T F < 0. \qquad (16)$$

The below figure shows the Block diagram of the proposed adaptive voltage controller

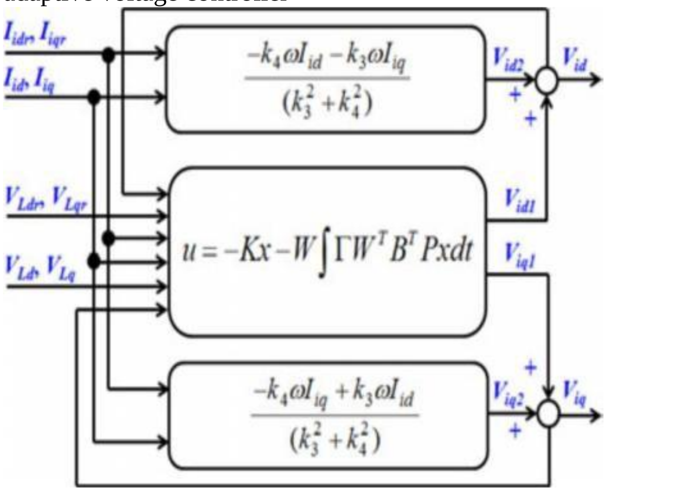


Figure.3. Block diagram of the proposed adaptive voltage controller

II. ULTRA-CAPACITOR AND BIDIRECTIONAL DC-DC CONVERTER

In this paper, the equivalent circuit of ultra- capacitor model as reported in [13, 21] is applied to simulate the ultra-capacitor. As represented in Fig.4, the model consists of a capacitance *uc C,* an equivalent parallel resistance *p R,* and an equivalent series resistance *s R.*

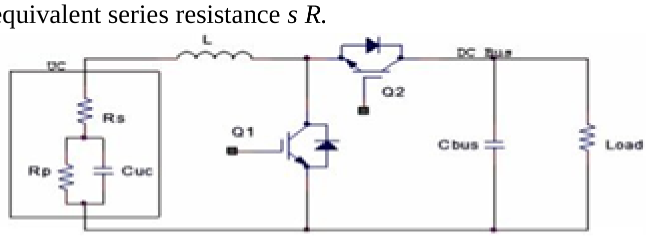


Figure.4. The electrical circuit of ultra-capacitor-bidirectional DC-DC converter topology

To realize the reversible direction of power flow in bidirectional DC-DC converters, the switch should ideally carry the current in both directions. Therefore, it is usually implemented with a unidirectional semiconductor power switch connected in parallel to a diode. In the first direction, the converter transfers the energy from the ultra-capacitor to the DC bus when starting up the renewable generation system, and during the transient load conditions. When there is an excess energy at the DC bus, the converter charges the ultra-capacitor in its low-side. The used parameters for the converter and the ultracapacitor are listed in Table I. The initial voltage of the ultracapacitor is 100V.According to literature, the buck charging and boost discharging current modes share the same power plant transfer function; therefore, sharing a unified controller is tolerable. The unified controller concept means one controller can be used for both switches, whereby they are controlled in a complementary fashion. In this work, the boost mode of operation is selected for the purpose of designing the controller. Hence, the small-signal model of the boost converter is derived. Similar to the study made in [25], the renewable energy source is modeled as a current source connected to the DC bus. Table II gives the nominal parameters for simulations.

Table.1. Parameters of the uc simulated system

L (mH)	C (µF)	Ro (Ω)	Vo (V)	Cuc (F)	Rs (mΩ)	Rp (Ω)
0.1	150	32	280	165	7	1×10^{9}

Table .2 Nominal Parameters

Items	Values
DGS rated power (P_{rated})	450VA
dc-link voltage (V_{dc})	280V
Load output voltage ($V_{L,rms}$)	110V
Output frequency (f)	60Hz
Switching and sampling frequency	5kHz
LC output filter	L_f = 10mH, C_f = 6µF
Resistive load/unbalanced load	R_L = 80Ω
Nonlinear load	C_{dc} = 3300µF, R_{dc} = 500Ω

Table .3. Summary of simulation results in steady-state analysis

The proposed adaptive voltage controller				
Load types	Load output voltages (V_{rms})			THD (%)
	V_{LAn}	V_{LBn}	V_{LCn}	
No load	109.9	109.7	109.8	0.04
Balanced load	109.3	109.5	109.4	0.04
Unbalanced A&B load	109.7	109.9	109.3	0.04
Nonlinear load	108.5	108.6	108.4	0.38
The non-adaptive voltage controller				
Load types	Load output voltage (V_{rms})			THD (%)
	V_{LAn}	V_{LBn}	V_{LCn}	
No load	108.5	108.5	108.6	0.37
Balanced load	108.3	108.6	108.4	0.37
Unbalanced A&B load	108.6	108.5	108.3	0.41
Nonlinear load	107.9	107.7	107.8	1.30

IV. SIMULATION RESULTS

In the paper, simulations are carried out to verify the effectiveness of the proposed adaptive control algorithm under the following four conditions:

1) Balanced load (0%→100%): The balanced resistive load is instantaneously applied to the inverter output terminals.
2) Balanced load (100% → 0%): The balanced resistive load is instantaneously removed from the inverter output terminals.
3) Unbalanced load: The unbalanced resistive load is connected to the inverter output terminals, i.e., only phase C is opened.
4) Nonlinear load: A three-phase full-bridge diode rectifier is connected to the inverter output terminals. It is also connected in parallel with a capacitor (Cdc) and a resistor (Rdc), and the nonlinear load has a crest factor of 2.25:1. Conditions 1 and 2 show the transient responses when the load instantaneously changes with a step. On the other hand, conditions 3 and 4 show the steady-state responses when the unbalanced load and nonlinear load are applied

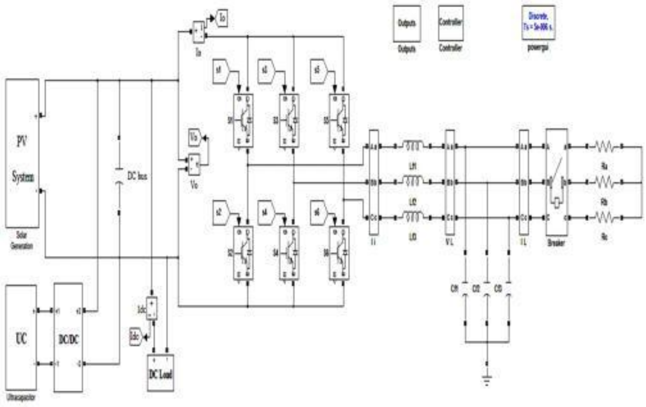


Figure.5. simulation diagram of the proposed system with ultra- capacitor and PV system

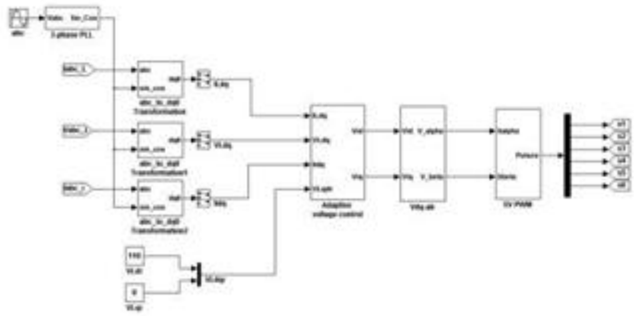


Figure.6. proposed controlling circuit with adaptive voltage controller

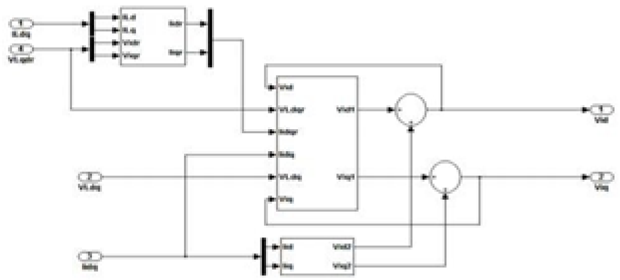
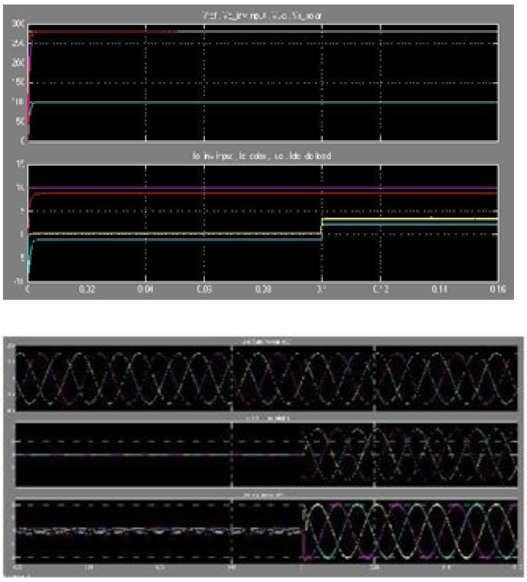
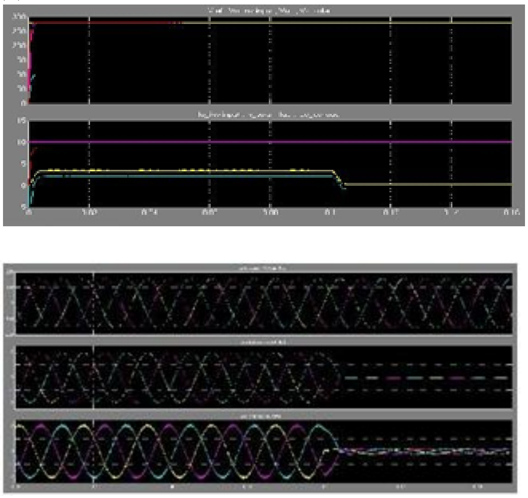


Figure.7.adaptive voltage controller

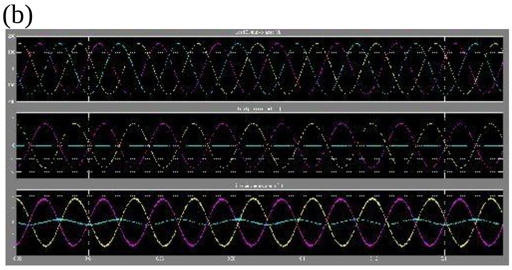
Fig. 8 shows the simulation results of the proposed Inverter system with ultra-capacitor and PV system and adaptive voltage controller using Matlab/Simulink under four different conditions mentioned previously. Figs. 8(a) through 8(d) show the waveforms of Reference DC voltage (Vref), Inverter input dc voltage (Vdc), Ultracapacitor voltage (Vuc), PV voltage (Vpv), Inverter input dc current (Idc), PV current (Ipv), Ultracapacitor current (Iuc), dc load current (Idc_load), load output voltages (VL_abc), load phase currents (IL_abc), and Inverter phase currents (Ii_abc), respectively. In Fig. 8(a) and (b), it is observed that the distortions of the load output voltage waveforms are negligible during the transient when a resistive balanced load is instantaneously applied to or removed from the inverter output terminals (i.e., 0% to 100% or 100% to 0%) because the load voltage wave forms are recovered within a short time of 0.4 ms. In Fig. 8(c) and (d), it is also seen that the THDs in the load output voltage waveforms are 0.04% and 0.38% under the unbalanced load and nonlinear load, respectively.



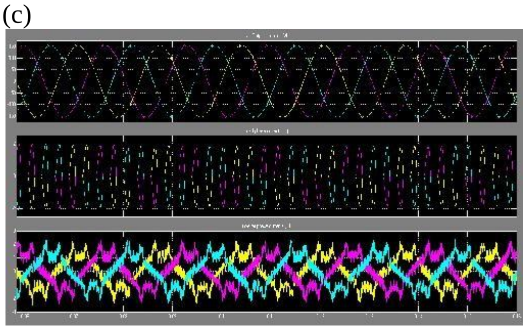
(a)



(b)



(c)



(d)

Figure.8. Simulation results of the proposed Inverter with PV and Ultracapacitor system (a) Balanced resistive load (0% to 100%). (b) Balanced resistive load (100% to 0%). (c) Unbalanced resistive load. (d) Nonlinear load.

V. CONCLUSION

This paper presents an Adaptive voltage control theory for the three phase system, which is feeded by PV system. An ultra-capacitor is interfaced for the proposed system through a DC-DC converter. Ultra-capacitors are used to improve the system's reliability and energy conversion efficiency. And also the disturbances in the DC output of the PV panels will be reduced and the DC input to the three phase inverter system will maintain constant. This proposed adaptive voltage control strategy has shown exceptional voltage regulation performance under various types of loads. The simulation results presented under the parameter uncertainties and are compared to the performances of the corresponding non-adaptive voltage controller in table –III.

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