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Buck-Boost Control of Four Quadrant Chopper using Symmetrical Impedance Network for Adjustable Speed Drive

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ABSTRACT

This paper proposes buck-boost capabilities of four quadrant chopper for wide range speed control of DC motor drives using symmetrical impedance network called Z-source network. By controlling the shoot through duty ratio from 0 to 0.5 and non-shoot through techniques, the Z-source four quadrant choppers can produce any desired DC voltage across the DC motor. The switching patterns for both buck and boost operations are presented to achieve four modes of operation of DC motor. As a result, the proposed model will have ride through capability during voltage sags, manage during voltage swells, used in any types of DC voltage sources such as fuel cell and solar cell and improve the reliability by reducing EMI noise. Analysis and simulation results are presented to demonstrate these new findings.

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1. INTRODUCTION

DC motor/permanent magnet DC motor has been playing an important role in different applications because of easy and wide range of speed and torque control. In all above applications four quadrant operations of DC motor are required in order to achieve forward motoring mode, forward regenerative braking mode to feedback the energy to system, reverse motoring mode and reverse regenerative braking mode. It is a buck (or step-down) converter that can only produce an output voltage across armature limited by the input dc link voltage. Therefore, the voltage rating of motor must be same as the input voltage. The selection of motor voltage rating is based on the input voltage. Voltage sag is the power quality related problems which is momentary in nature(about 2 seconds) and a maximum reduction of input voltage by about 50% can interrupt four quadrant chopper based adjustable speed dc drive system and shut down critical loads and processes. The dc link capacitor on input side is a relatively small energy storage element and is not capable to keep the voltage constant. Lack of ride-through capability is a serious problem for sensitive loads driven by four quadrant chopper circuit [1]-[3]. EMI noise is the major problem in four quadrant chopper circuit in terms of reliability and performance [4]. A recently developed new symmetrical impedance network named as Z-source inverter is use to overcome the aforementioned problems. Its classical control technique and the parasitic element like ESR are analyzed for the better performance and wide applications like centrifugal pump [5]-[8]. Because of buck capability of four quadrants chopper based adjustable speed dc drive, fuel cell /solar cell cannot be used as a source of the system. This is because fuel cells usually produce a voltage that changes widely (2:1 ratio) depending on current drawn from the stacks. Also, the solar cell voltage variation is 70 to 85% of the nominal temperature and radiation depending on MPP point temperature and radiation [9]-[14]. Performance and reliability are affected by the four quadrant chopper circuit because of miss-gating from EMI can cause shoot-through(two semiconductor switches of one leg are on at the same time) that damages the chopper circuit [15]-[19]. To overcome the first three aforementioned problems, a boost dc-dc converter (step-up converter) can be incorporated in between input source and four quadrant chopper. However, use of one extra self commutated semiconductor switch increases cost and EMI noise [20]-[22]. This paper uses symmetrical impedance network consisting of two equal valued inductors and capacitors arranged in Z-form and battery as input source, and proposes the control technique of semiconductor switches to operate the dc machine in all the four quadrants at desired speed. A Z-source based four quadrant dc chopper for adjustable speed dc motor drive can produce any desired output armature dc voltage, even greater or less than the input dc voltage. This implies that the circuit shown in Figure 1 has both buck and boost capabilities. Provide ride-through during voltage sags and compensate voltage swell without any additional semiconductor switch and Reduce EMI noise. The equivalent circuit in buck and boost mode has also been analyzed. Simulation has been carried out to prove the concept using MATLAB/SIMULINK.

2. ANALYSIS OF Z-SOURCE FOUR QUADRANT CHOPPER FOR BOOST MODE

As seen in Figure 1, the Z-source based four quadrant dc chopper for adjustable speed control dc motor drive utilizes symmetrical impedance network consisting of two inductors and two capacitors to link the four quadrant dc chopper to input dc supply. Here battery is used as the input. The 4 different modes of operations are explained [23]-[25].

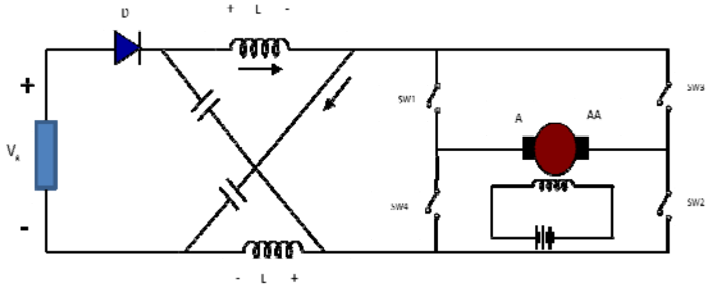

Figure 1. Four quadrant of chopper using Z-source impedance network

2.1. Forward Motoring Mode

Operation of the circuit assuming continuous conduction mode can be explained through two modes. The active state occurs when SW1 and SW2 are turned on. In this mode, the diode D5 is forward biased and therefore input is connected to load. The shoot through state occurs when SW1, SW4 and SW2 are turned on. Due to sudden change of switching action, the diode D5 is reverse biased and therefore the input is disconnected from the load.

The voltage relations under active state are:

$$v_L(t) = v_b(t) - v_C(t) \tag{1}$$

$$v_{dc}(t) = v_{dcn}(t) = v_C(t) - v_L(t) = 2v_C(t) - v_b(t) \tag{2}$$

The voltage relations under shoot-through state are:

$$v_L(t) = v_C(t) \tag{3}$$

$$v_{dc}(t) = 0 \tag{4}$$

Where $v_L(t)$,$v_C(t)$, $v_b(t)$, $v_{dc}(t)$ and $v_{dcn}(t)$are inductor, capacitor, battery, input to four quadrant chopper and non-zero portion of $v_{dc}(t)$voltages respectively.

The average voltage input to four quadrant chopper over the switching period is:

$$V_{dc}(t) = (1 - d)v_{dcn}(t) \tag{5}$$

Where d is the duty cycle of the *SW2* or *SW4*.

It is also shown using steady-state analysis that the average voltage input to four quadrant chopper is equal to capacitor voltage. Substituting (2) in (5) and replacing $v_c(t)$ by $v_{dc}(t)$,

$$V_a(t) = V_{dc}(t) = \frac{(1-d)}{(1-2d)} v_b(t) \tag{6}$$

Where $V_a(t)$ average voltage across the armature.

The peak voltage across armature is:

$$V_p(t) = \frac{1}{(1-2d)} v_b(t) \tag{7}$$

In the range, *0≤d≤0.5*, Z-source converter will act as boost chopper and above 0.5 to 1 it will act as both buck and boost chopper with reverse polarity of output voltage. The buck and boost capabilities of Z-source converter is shown in Figure 2. The buck and boost capabilities of Z-source converter can be achieved only when diode *D5* is replaced by self commutated semiconductor control switch. To achieve the above mentioned capabilities the shoot-through switch and replaced switch must be complimentarily triggered. But the valid range of duty cycle of Z-source converter using diode to connect or disconnect source to load is *0≤d≤0.5*. Above 0.5 the diode is forward biased because of reverse polarity of output voltage and therefore, the source gets connected during shoot through state which may damage the switches.

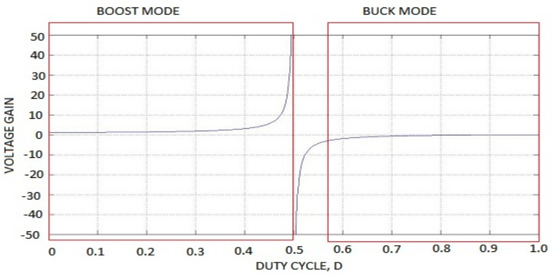

Figure 2. Buck and Boost capabilities of Z-source Converter

Without shoot-through state (*d=0*) Z-source impedance network has no impact on the input voltage to the four quadrant chopper and it is same as the battery voltage, so that buck mode using diode can be easily achieved using different patterns. Due to parasitic elements inherent in inductor, capacitor and switches the output voltage is limited to 5 to 10 times of input voltage depending upon the value of parasitic elements. The peak voltage across the armature (rate of change of voltage) depends upon shoot-through ratio. Let us consider the shoot-through ratio is 0.45 to boost the average voltage to 5.5 times the input voltage. The rate of change of the armature voltage is 10 times of input voltage which creates the deleterious effect of causing high dielectric loss in the insulation and therefore reduced life. In addition, it produces high stresses on switches.

In this mode the speed of the motor can be controlled above the speed produced by the battery voltage by controlling the duty ratio in the range of *0≤d≤0.5*.

2.2. Forward Regenerative Braking Mode

In this mode, the direction of armature current reverses and therefore, the motor acts as a generator. Here one of the switch *SW4* or *SW3* is turned-on and off to move from one state to another. When *SW4* is on the armature current is circulated through *SW4* and *D2*. In this state, the energy stored in the armature inductance releases through the armature resistance. When *SW3* is turned-off, the diodes *D1* and *D2* conduct and power is fed back to impedance network. The voltage relations are:

$$V_a(t) = 0(\mathit{SW3}\text{turned-on}) \tag{8}$$

$$V_a(t) = V_b(t)(\text{Diodes } \mathit{D1} \text{ and } \mathit{D2} \text{ conducting}) \tag{9}$$

2.3. Reverse Motoring Mode

In reverse motoring mode for boost operation, the active state occurs when *SW3* and *SW4* are turned on. The diode *D5* is forward biased and therefore, the load is connected to input. The shoot through state occurs when *SW2*, *SW3* and *SW4* are turned on which reverse biased the diode *D5*, thereby, disconnecting the load from the input. The mathematical analysis is same as the forward motoring mode. The average voltage across the armature is:

$$V_a(t) = V_{dc}(t) = -\frac{(1-d)}{(1-2d)} v_b(t) \text{for } 0 \leq d \leq 0.5 \tag{10}$$

The negative speed of the motor can be controlled above the speed produced by the battery voltage by controlling the duty ratio in the range of *0≤d≤0.5*.

2.4. Reverse Braking Mode

To send the power to the source the motor must act as generator by reversing the direction of reverse motoring armature current. This is achieved by turning on and off either one of the switches *SW1* or *SW2*. When *SW2* is on the armature current is circulated through *SW2* and *D4*.In this state, energy stored in the inductance of armature discharges. When *SW1* is turned-off, diodes *D3* and *D4* conduct and power is fed back to the impedance network. The voltage relations are:

$$V_a(t) = 0(\mathit{SW1}\text{turned-on}) \tag{11}$$

$$V_a(t) = V_b(t)(\text{Diodes}\mathit{D3}\text{and}\mathit{D4}\text{conducting}) \tag{12}$$

3. ANALYSIS OF Z-SOURCE FOUR QUADRANT CHOPPER FOR BUCK MODE

As diode *D5* is used in this paper, the valid range of d is 0 to 0.5. Buck capability can be achieved without using shoot through technique. In buck mode, the impedance network remains inactive to voltage input to the four quadrant chopper. The operations of forward motoring mode and reverse motoring mode are briefly described referring Figure 1.

3.1. Forward Motoring Mode

In this mode there are two states (assuming continuous conduction mode). The switch *SW1* or *SW2* is always operated by gating on in both the states as long as forward motoring mode is required. Assume that *SW2* is on in both the states. By switching on and off *SW1*, we can transfer from one state to another. The input source is connected to the armature of the motor terminals through the *SW1* and *SW2* in active state. By removing the gate pulse in switch *SW1* (non-active state), the armature current is circulated through *SW2* and *D4* and in armature winding. In this state the energy stored in the armature is released. The voltage relation in active state is:

$$v_a(t) = v_b(t) \tag{13}$$

The voltage relation in non-active state is:

$$v_a(t) = 0 \tag{14}$$

The average voltage across the armature is:

$$V_a(t) = dv_b(t) \tag{15}$$

Where d is the duty ratio of *SW2*. The speed of the motor can be controlled below the speed produced by the battery voltage by controlling the duty ratio.

3.2. Forward Regenerative Braking Mode

The procedure is same as the forward motoring mode except that the polarity of armature voltage is negative. This mode is achieved by switching on and off the switches *SW3* and *SW4*. One of the switches is always operated as long as reverse mode is required. By switching on and off *SW4*, if *SW3* is continuously on, the state can be changed. In active state, the current flows through the load via *SW3* and *SW4*.The current is circulated in the load by *SW3* and *D1* in non-active state.

The voltage relation in active state is:

$$v_a(t) = -v_b(t) \tag{16}$$

The voltage relation in non-active state is:

$$v_a(t) = 0 \tag{17}$$

The average voltage across the armature is:

$$V_a(t) = -dv_b(t) \tag{18}$$

The negative speed of the motor can be controlled below the speed produced by the battery voltage by controlling the duty ratio. Forward regenerative braking and reverse regenerative braking are same as the boost mode.

4. SIMULATION RESULTS

Simulation has been performed in buck and boost modes using separately excited motor to confirm the above analysis. The values of parameter are set based on the limitation of ripple in current (L) and ripple in voltage(C). The simulation is set up using MATLAB/SIMULINK environment with the following parameters.

1) Battery voltage (nominal): 52.26 V.

2) Prime mover: Separately excited dc motor 5HP, 240V with R_a=2.581ohm, L_a=0.028H, L_{af}=0.9483H, V_f=300V, $R_{F=}$281.3ohm, L_f =156H, J(Moment of inertia)=0.2215 Kg-m^2, B(Viscous friction coefficient)=0.002953N-s/rad, T_c(coulomb friction)=0.5161N-m and No-load speed=183.16rad/sec.

3) Z-source network: L= 10 mH and C= 1mF

4) Switching frequency: 10 kHz.

The gating patterns for the switches to operate the machine in four quadrant buck and boost mode are shown in Figure 3 and Figure 4 respectively.

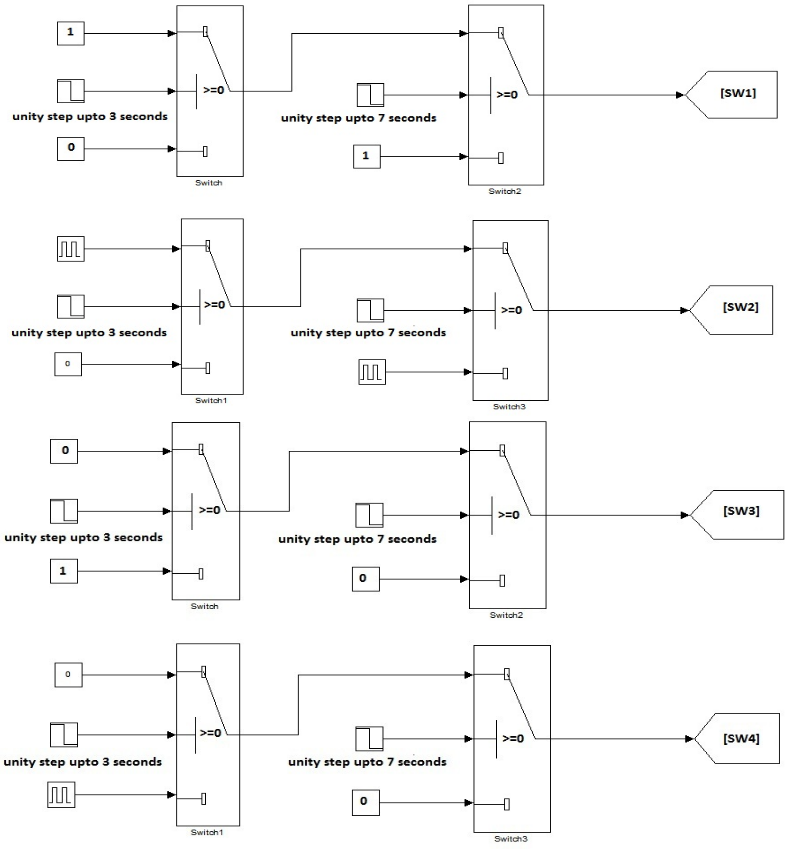

Figure 3. Gating patterns for buck four quadrant operation of dc motor drive using MATLAB/SIMULINK

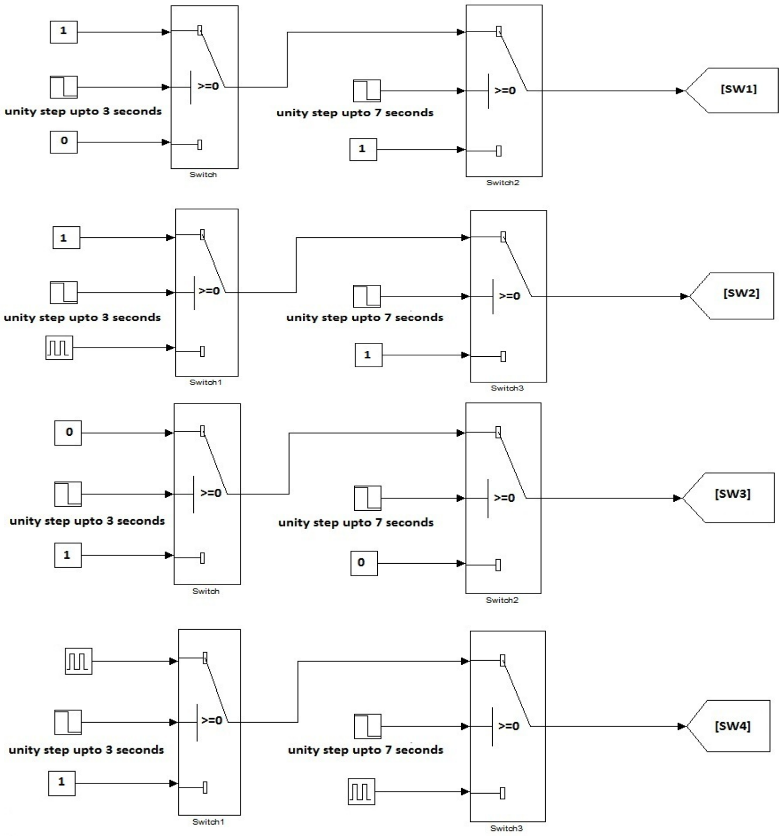

Figure 4. Gating patterns for boost four quadrant operation of dc motor drive using MATLAB/SIMULINK

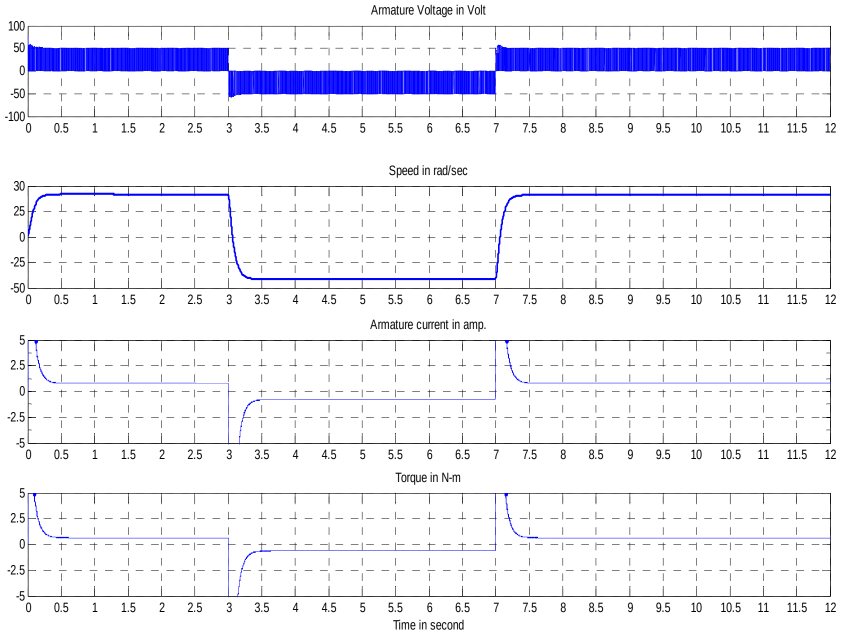

Figure 5. Simulation results of four quadrant operation of dc motor in buck mode using duty ratio 0.7

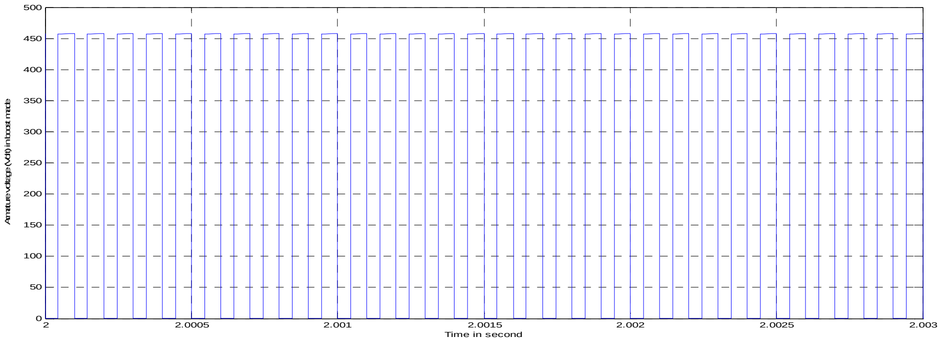

Figure 6. Enlarge figure of armature voltage in boost and buck mode

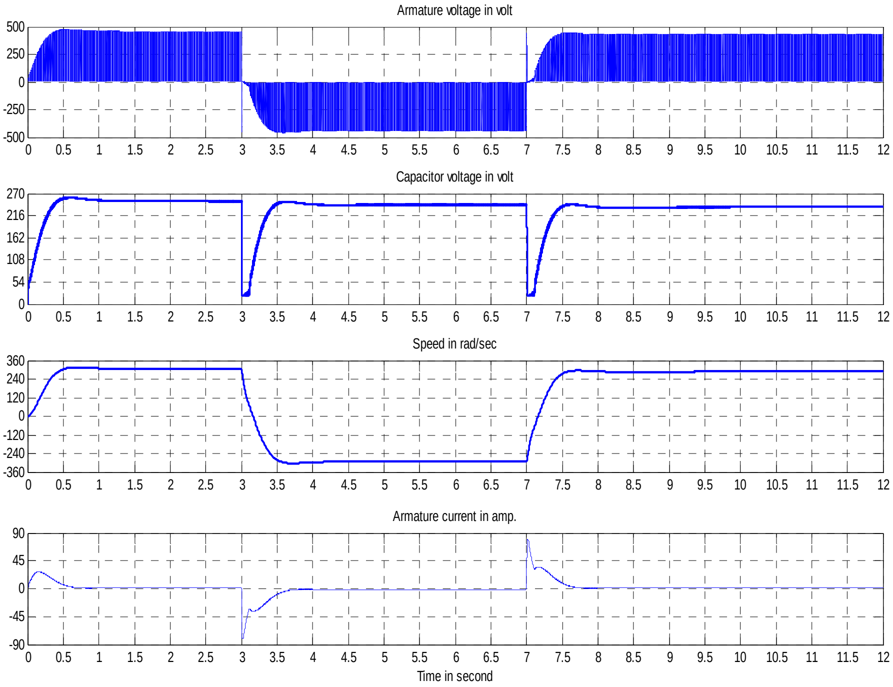

Figure 7. Simulation results of four quadrant operation of dc motor in boost mode using shoot-through duty ratio 0.4

Forward motoring mode up to 3 second is followed by forward braking mode. Then reverse motoring mode up to 7 seconds is followed by reverse braking mode. Reverse braking and forward braking modes are applied to confirm the modes of operation and buck and boost capabilities of proposed control techniques. Figure 5 shows the armature voltage, speed, armature current and torque as dc motor operates in all the four regions in buck mode. The time of forward motoring is 0 to 3 second and 7.1 to 12 second. The forward regenerative braking and reverse regenerative braking time is only 0.1 second (3 to 3.1 second forward motoring and 7 to 7.1 second reverse braking). The time of reverse motoring is 3.1 to 7 second. The enlarge figure of armature voltage is shown in Figure 6 shows the buck and boost capability of four quadrant chopper. Figure 7 shows the armature voltage, capacitor voltage, speed and armature current of dc motor operates in all the four regions in boost mode. During braking mode, the voltage across the capacitor falls by large amount and transfers energy to the inductor. The armature current also rises sharply to 48A. As the braking time increases, the capacitor starts building up the voltage and armature current starts falling. The forward and reverse braking is about 0.2 second.

5. CONCLUSION

This paper has proposed new switching patterns techniques for controlling the speed of the dc machine in wide range and operated in four possible modes even though input dc voltage is less than voltage rating of dc machine using Z-source impedance network. The Z-source four quadrant dc choppers employs a symmetrical impedance network to couple the four quadrant chopper circuit to dc power source thus providing unique features that cannot be obtained in the traditional voltage-source and current-source four quadrant choppers. The control, configuration and operating principles of the model are analyzed in detail. Simulation results are presented the applicability of this proposed noble control technique.

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