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A New Method for Voltage and Frequency Control of Stand-Alone Self-Excited Induction Generator Using PWM Converter with Variable DC link Voltage

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Abstract **Three-phase self-excited induction generators (SEIG) play an important rule in renewable energy sources such as wind and hydraulic energy. Their main disadvantage is poor voltage and frequency regulation under varying load and speed. This paper introduces a new and simple method for voltage and frequency control of three-phase unregulated speed induction generators in the islanding mode. The method uses a constant voltage constant frequency (CVCF) PWM converter without regulating the DC capacitor voltage. The capacitor voltage is left changing with the loading conditions and the AC side voltage is regulated by controlling the modulation index. This eliminates the need of an auxiliary switch in the DC side which reduces the cost and also reduces the high frequency current components flowing in the DC capacitor and that increases its life time. The proposed technique is tested under step changes in load and prime mover speed. The proposed technique gives the same response as the old technique but without the use of DC side switch.**

Index Terms **Self-Excited induction generators (SEIG), Constant voltage constant frequency (CVCF) operation, Electronic load controller (ELC), PWM converter.**

I. INTRODUCTION

Distributed power generation has received greater attention in recent years for use in remote and rural communities. Self-excited induction generators have been widely used during the last decades in renewable electric generation especially in wind energy conversion systems (WECS) and hydraulic energy applications in remote isolated areas. Squirrel-cage rotor induction machines are preferred for its reduced cost, robustness, absence of separate source for excitation, and ease of maintenance compared with dc and wound-rotor synchronous machines. Despite these favorable features, induction generators have unsatisfactory voltage and frequency regulation with variation in load (magnitude and power factor) and speed [1]. When induction generator (IG) is directly connected to the grid, it starts generating power when its rotor is driven by a prime mover at a speed higher than the synchronous speed determined by the frequency of the grid voltage. Its output voltage and frequency is fixed at the grid voltage and frequency. This is not the case when the generator is stand alone. The voltage build-up is initiated either by the generator residual flux or by pre-charging the excitation capacitors. The steady state voltage and frequency depends on the value of the excitation capacitors, the electrical load, the magnetization characteristics and the prime mover speed. The electrical load is continuously changing by nature as well as the prim-mover speed. Thus, it is not an easy task to regulate the voltage and frequency of self excited induction generators. It should be highlighted that the voltage drops at the stator and rotor resistances and leakage reactances are not the main cause of the poor voltage and frequency regulation. Rather, the fundamental factor is the influence of the frequency on the generator magnetization characteristic. Conventionally, a speed governor is employed for the regulation of the prime mover [2]. The speed governor is generally quite expensive and due to its large mechanical time constant, is unable to react fast enough to transients. Pitch angle control is also used in case of wind turbines [3]. In [4] voltage and frequency control have been established using switched resistances and a thyristor controlled reactor (TCR) which leads to harmonic currents in the stator of the induction generator. The outstanding evolution experienced by power semiconductor devices and power converter technology has made a breakthrough in the control of SEIG. In the literature, many techniques have been developed to control the SEIG using PWM converters. The vast majority of them is concerned with voltage regulation [5:9] and a few of them discuss the frequency control [10:20]. Although the frequency may be allowed to vary in isolated areas, some loads such as computers, power supplies and variable speed drives are sensitive to changes in frequency. The AC/DC/AC connection [10], doubly fed induction generators (DFIG) [11, 12] and matrix converters are used to regulate voltage and frequency of SEIG. These methods require the use of two back-to-back high rated PWM converters which increases the cost of the system and the complexity of the control. A number of lower cost schemes with a single power electronic converter have been proposed in the literature. In [13], voltage and frequency of slip-ring induction generator are controlled by varying the effective rotor resistance using a DC chopper. But this introduces current harmonics in the rotor circuit and the slip-ring machine is more expensive and requires more

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maintenance. In [14:18] the concept of electronic load controller (ELC) is used by connecting the stator terminals to a controlled or uncontrolled rectifier with a capacitor and DC chopper in the DC side. By controlling the chopper switch, the excess in the generated electrical power is consumed in the ELC so that the active power load seen by the generator is always constant and thus maintaining the voltage and frequency. Although simple, this technique injects harmonic currents into the stator and it is unable by nature to compensate for changes in the load reactive power. In [3, 19 and 20] voltage and frequency control is achieved using PWM voltage source converter with a capacitor and a chopper in the DC side. The control objective is to maintain the DC voltage constant by changing the effective value of the DC resistance to consume the excessive generated power. By maintaining a constant modulation index, the AC voltage can be maintained constant. Although simple, this technique uses an extra switch in the DC side which increases the system cost and injects harmonic current components in the DC capacitor which decreases its life time. Also, magnetic saturation was not included in simulation and the magnetizing inductance was assumed constant. In this paper, a new simple technique is proposed using a PWM converter without a chopper on the DC side. The dc voltage is left without regulation. However, the modulation index is regulated to maintain a constant voltage at the induction generator terminals. The paper is organized as follows. In Sec. II, the mathematical models of the system components are given. Sec. III discusses the technique used in [3, 19 and 20]. In Sec. IV, the proposed technique is discussed in detail. The simulations of both techniques under sudden change in both load and speed are given in Sec. V.

II. The System Model

a) The induction generator model:

The three phase SEIG is modeled in stationary reference frame using the following equations [21, 22]:

$$v_{sd} = -i_{sd} Rs + \frac{d\lambda_{sd}}{dt} \tag{1}$$

$$v_{sq} = -i_{sq} Rs + \frac{d\lambda_{sq}}{dt} \tag{2}$$

$$v_{rd} = -i_{rd} R_r + \frac{d\lambda_{rd}}{dt} + \omega_r \lambda_{rq} \tag{3}$$

$$v_{rq} = -i_{rq} R_r + \frac{d\lambda_{rq}}{dt} - \omega_r \lambda_{rd} \tag{4}$$

$$\lambda_{sd} = -L_s\, i_{sd} + L_m\, i_{rd} \tag{5}$$

$$\lambda_{sq} = -L_s\, i_{sq} + L_m\, i_{rq} \tag{6}$$

$$\lambda_{rd} = -L_r\, i_{rd} + L_m\, i_{sd} \tag{7}$$

$$\lambda_{rq} = -L_r\, i_{rq} + L_m\, i_{sq} \tag{8}$$

where

$v_{sd}, v_{sq}, v_{rd}, v_{rq}$ are stator and rotor voltages in d-q axis.

$i_{sd}, i_{sq}, i_{rd}, i_{rq}$ are stator and rotor currents in d-q axis.

$\lambda_{sd}, \lambda_{sq}, \lambda_{rd}, \lambda_{rq}$ are stator and rotor flux linkages in d-q axis.

R_s, R_r, L_s, L_r are stator and rotor resistances and self inductances

L_m is the mutual inductance between stator and rotor

Due to magnetic saturation, the magnetizing inductance L_m is not constant but is a nonlinear function of the magnetizing current i_m. i.e

$$L_m = f(i_m) \text{ where } i_m = \sqrt{(-i_{sd} + i_{rd})^2 + (-i_{sq} + i_{rq})^2} \tag{9}$$

b) TheR-L load model

The load model in the stationary frame is given by:

$$\frac{di_{ld}}{dt} = \frac{1}{L_l}(v_{sd} - i_{ld} R_l) \tag{10}$$

$$\frac{di_{lq}}{dt} = \frac{1}{L_l}(v_{sq} - i_{lq} R_l) \tag{11}$$

where

i_{ld}, i_{lq} are load currents in d-q axis, and

R_l, L_l are load resistance and inductance

c) The PWM converter model:

The model of the PWM converter in stationary frame is:

$$\frac{di_{cd}}{dt} = \frac{1}{L_c}(v_{sd} - i_{sd}\, R_c - v_{cd}) \tag{12}$$

$$\frac{di_{cq}}{dt} = \frac{1}{L_c}(v_{sq} - i_{sq}\, R_c - v_{cq}) \tag{13}$$

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc} v_{dc}}(v_{sd}\, i_{cd} + v_{sd}\, i_{cd}) - \frac{v_{dc}}{C_{dc} R_{dc}} \tag{14}$$

where

i_{cd}, i_{cq} are inverter currents in d-q axis.

v_{cd}, v_{cq} are the inverter voltages in d-q axis.

R_c, L_c are inverter interfacing resistance and inductance.

C_{dc} is the DC side capacitor, and

v_{dc} is the DC capacitor voltage

In sinusoidal pulse width modulation, at steady state, the peak of the fundamental AC voltage at the inverter terminals V_c is given as:

$$V_c = \frac{1}{2} M v_{dc} \tag{15}$$

where M is the modulation index

d) The excitation system model:

The excitation system model in stationary reference frame is given as:

$$\frac{dv_{sd}}{dt} = \frac{1}{C_{ac}}(i_{sd} - i_{ld} - i_{cd}) \tag{16}$$

$$\frac{dv_{sq}}{dt} = \frac{1}{C_{ac}}(i_{sq} - i_{lq} - i_{cq}) \tag{17}$$

where C_{ac} is the AC side capacitor

III. The Constant DC Link Voltage Technique

The constant DC link voltage system as shown in Fig. 1 comprises an induction generator excited by a three-phase capacitor bank and a pulsewidth modulation (PWM) voltage-fed PWM inverter. The IG is connected to the PWM inverter ac side through filter inductances. The value of the inverter AC voltage can be made constant if both the DC voltage and the modulation index do not vary. The exceeding power can be consumed by a controllable load which is a dumping resistance situated in the dc side of the PWM inverter enabling the total power supplied by the generator to match the sum between the consumer's loads and dump load. The DC voltage is the feedback signal which reflects the balance between the generated and the consumed power. An increase in v_{dc} indicates that the electric power generated is higher than the power of the ac load connected to the IG. Conversely, a decrease in v_{dc} indicates a deficit in the generated power. The second-order low-pass filter composed of L_c and C_{ac} guarantees sinusoidal waveform at the IG leads. The cut off frequency f_c is calculated as follows:

$$f_c = \frac{1}{2\pi\sqrt{L_c C_{ac}}} \tag{18}$$

The control is attained by comparing the v_{dc} sample with a reference using a hysteresis comparator as shown in Fig. 2. The hysteresis limits should be set to maintain v_{dc} in an allowable variation range, in order to avoid voltage variation (flicker effect) in the ac side. The DC resistance is switched on when the DC voltage exceeds $v_{\max}$ and, once connected, to be switched off when the dc voltage returns to $v_{\min}$. Thus, the system's power balance is reduced to the DC capacitor voltage control.

IV. The Variable DC Link Voltage Technique

In the proposed technique, the DC link voltage is left without regulation. When the electrical load increases, this increase is supplied instantaneously from the PWM converter which leads to a decrease in the DC link voltage. Conversely, when the electrical load decreases the excess power generated by the IG is instantaneously consumed in the PWM converter which increases the DC link voltage. In both cases, from (15), the modulation index must be updated in order to have constant AC voltage at the induction generator terminals as follows:

$$M = \frac{V_p^*}{\frac{1}{2} v_{dc}} \tag{19}$$

where V_p^* is the reference peak AC phase voltage

Taking into account that the electrical transients are much faster than the mechanical transients, the DC link voltage and the modulation index change and the system returns to its steady state power balance before any change in rotor speed occurs. The constant-frequency approach ensures that the steady-state operation of the IG will take place following only one magnetizing characteristic curve. In this method, the DC resistance should be properly designed. The DC resistance should have a maximum value that will not allow the DC link voltage to rise above the maximum rating of the DC side capacitor. The worst case for this situation is at no load where the whole active power generated has to be consumed in the PWM converter, i.e. in the DC resistance. Also, the DC resistance should have a minimum value that will not let the DC link voltage decreases below twice the peak reference phase voltage as the maximum modulation index is unity (see equation (19)). Thus,

$$R_{dc\min} < R_{dc} < R_{dc\max}$$

a) Design for maximum DC resistance $R_{dc\max}$:

At, steady state, the maximum electric power generated by the induction generator $P_{\max}$ is calculated as follows:

$$P_{\max} = 3(V_1 / \sqrt{2})\, I_1 \cos\phi_1 \tag{20}$$

$$\bar{I}_1 = \frac{V_p / \sqrt{2}\angle 0}{[R_s + jX_s + jX_m \,\|\, (R_r / S_{\min} + jX_r)]} = I_1 \angle \phi_1 \tag{21}$$

where

$X_s = 2\pi f_d L_s \quad X_r = 2\pi f_d L_r \qquad X_m = 2\pi f_d L_m$

f_d is the designed operating frequency

$s_{\min} = (\omega_d - \omega_{r\max}) / \omega_d \quad , \omega_d = 2\pi f_d / p$,

$\omega_{r\max}$ is the maximum expected rotor speed

p is the number of pair poles.

As this maximum power has to be consumed by the PWM converter at no load, then

$$P_{\max} = \frac{V_{dc\max}^2}{R_{dc\max}} \tag{22}$$

where $V_{dc\max}$ is the maximum voltage rating of the DC capacitor.

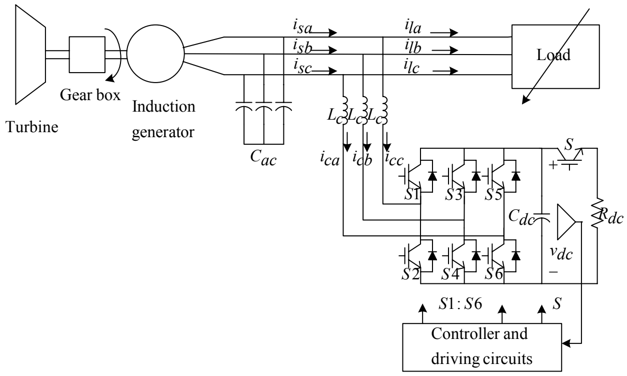


Fig.1 The constant DC link voltage configuration

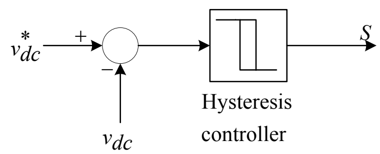


Fig. 2 The DC chopper control in constant DC voltage technique

b) Design for minimum DC resistance $R_{dc\,\min}$

The power consumed in the PWM converter will be minimum when the induction generator delivers its minimum output power $P_{\min}$ and the electrical load consumes its maximum power $P_{L\max}$, where

$$P_{\min} = 3(V_1 / \sqrt{2})\, I_2 \cos\phi_2 \tag{23}$$

$$\bar{I}_2 = \frac{V_p / \sqrt{2}\angle 0}{[R_s + jX_s + jX_m \parallel (R_r / S_{\max} + jX_r)]} = I_2 \angle \phi_2 \tag{24}$$

$s_{\max} = (\omega_d - \omega_{r\min}) / \omega_d$

$\omega_{r\min}$ is the minimum expected rotor speed

$$P_{\min} - P_{L\max} = \frac{V_{dc\min}^2}{R_{dc\min}} \tag{25}$$

$$V_{dc\min} = 2V_p^* \tag{26}$$

V. SIMULATION RESULTS

The conventional technique [3, 19, 20] and the proposed one are applied to voltage and frequency control of a 2 pole, 6 kW, three phase induction generator system with the following parameters:

$R_s = 3.75\,\Omega$ $\quad R_r = 5.22\,\Omega$

$L_s = 0.1744$ H $\quad L_r = 0.1786$ H

$C_{ac} = 300\,\mu$F $\quad C_{dc} = 2000\,\mu$F

$L_c = 2$ mH

The magnetization function is given by the following data:

i_m	0	20	40	60
L_m	0.1654	0.1354	0.12	0.10

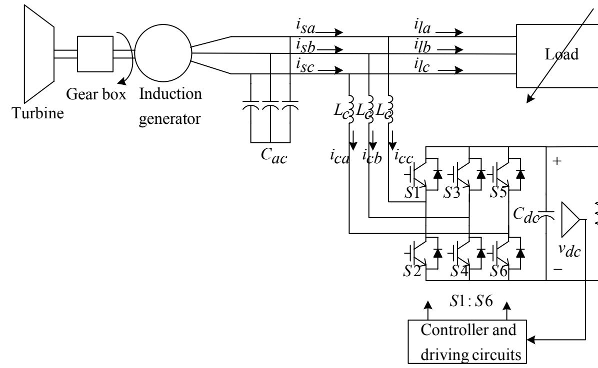


Fig. 3 The proposed variable DC link configuration

The design parameters are:

$V_p^* = 200$ V , $f_d = 18$ Hz $V_{dc\max} = 1100$ V

$P_{L\max} = 2400$ Watt $\omega_{r\max} = 157$ rad/sec

$\omega_{r\min} = 149$ rad/sec

Substituting in (20:26) gives:

$P_{\max} = 5194.6$ Watt $\quad P_{\min} = 4089.2$ Watt

$R_{dc\max} = 232.934\,\Omega$ $\quad R_{dc\min} = 195.637\,\Omega$

So, the chosen value for $R_{dc} = 200\,\Omega$

In the constant DC voltage technique, the reference voltage is 580 V and it is allowed to vary within a hysteresis band of +/-2V.

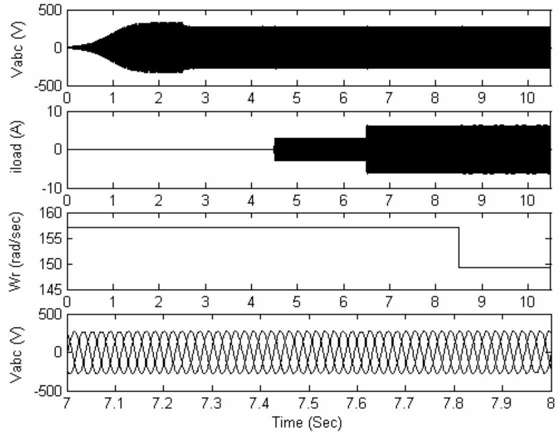
The sequence of simulation is as follows:

1- The three phase excitation capacitors are initially charged with 50 V, -25 V and -25 V respectively and the generator is driven at its maximum speed of 157 rad/sec.
2- The voltage build up process starts and the voltage and frequency reach steady state values due to magnetic saturation and the DC side capacitor is charged to nearly the peak generated line voltage through the freewheeling diodes.
3- The PWM converter is connected at t=2.5 sec.
4- A three phase resistive load of $100\,\Omega$ per phase is connected at t=4.5 sec.
5- A three phase inductive load of resistance $50\,\Omega$ per phase and inductance of 0.44 H per phase is connected at t=6.5 sec.
6- At t=8.5 sec, the driving speed is reduced to its minimum value of 149 rad/sec.

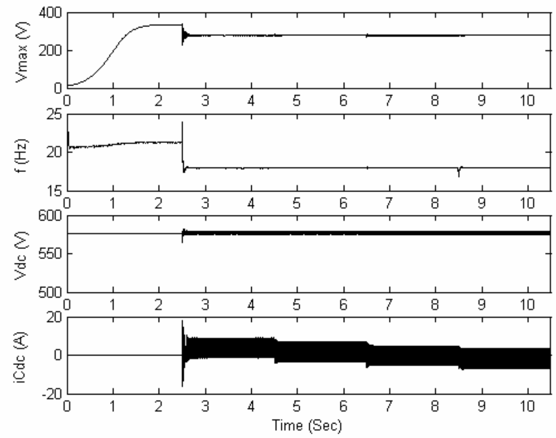
In the simulations, the frequency is calculated as [4]:

$$f = \frac{v_{sd}(dv_{sq}/dt) - v_{sq}(dv_{sd}/dt)}{v_{sd}^2 + v_{sq}^2} \tag{27}$$

Fig.4 shows the simulation results of the constant DC voltage technique and Fig. 5 shows the simulation results of the proposed (variable DC link voltage) technique. Fig 4(a) and Fig. 5(a) show the phase voltages, load currents and rotor speed. Fig. 4(b) and Fig. 5(b) show the peak phase voltage, the stator frequency, the DC voltage and DC link capacitor current. Fig. 4(c) and Fig. 5(c) show the variation of the magnetizing inductance. Fig. 4(d) and Fig. 5(d) show the inverter current. Fig. 5(b) shows also



(a)



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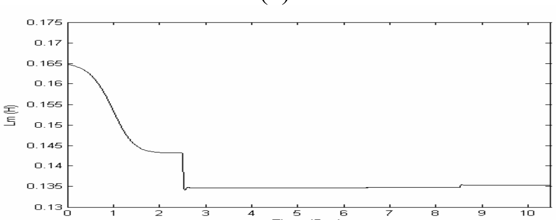
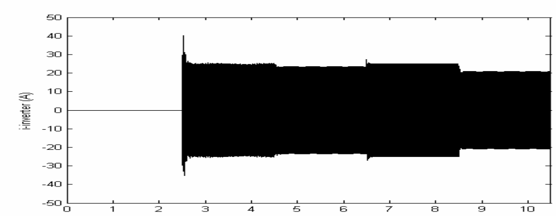
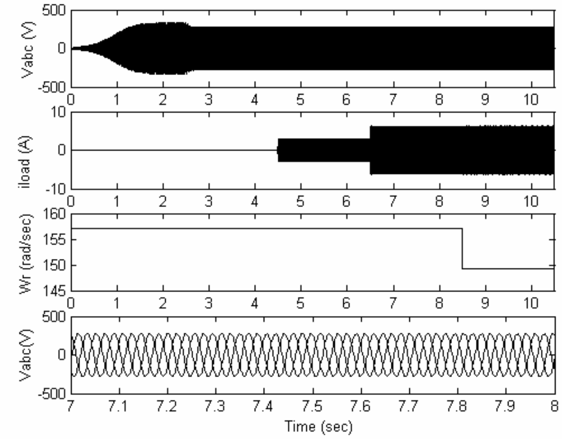


(c)

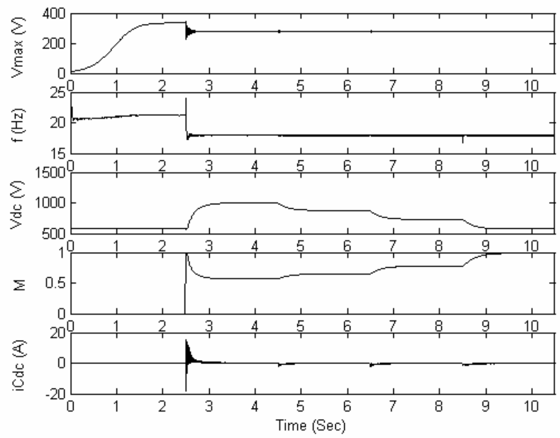


(d)

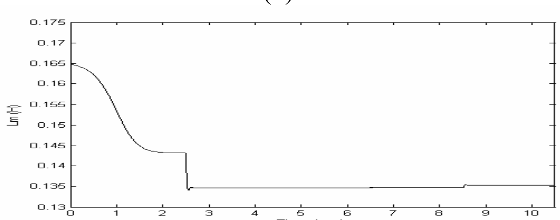
Fig. 4 Simulation of the constant DC voltage technique



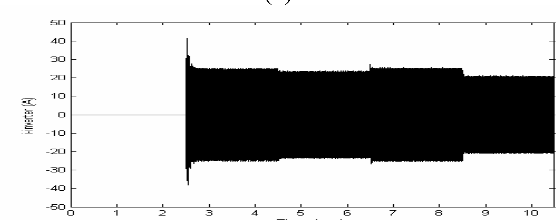
(a)



(b)



(c)



(d)

Fig.5 Simulation of the variable DC voltage technique the variation of the modulation index in the variable DC link voltage technique. It can be shown that the variable DC link voltage achieved the same excellent AC voltage and frequency tracking as the constant DC link voltage technique but without using an extra switch on the DC side. From Fig. 4(b) and Fig. 5(b), it is shown that by eliminating the DC side switch, the high frequency current components in the DC capacitor have been eliminated. Fig .4(d) and Fig 5(d) show that in both techniques, connection of the resistive load cause a decrease in the inverter current to maintain the active power balance. When connecting the inductive load, although the inverter active current component decreases, the compensating reactive current component of the inverter current leads to an overall increase in the inverter current magnitude. Since the excitation capacitor current is constant (because of the constant AC voltage), the reactive power demand of the load has been totally compensated by the PWM converter. When the driving speed is decreased, the generated power decreases and this decreases the inverter current as the load current remains constant. Fig. 5(b) shows that due to proper design of the DC resistance, neither the DC voltages nor the modulation index exceeds its maximum limit. In the constant DC voltage method, although the hysteresis band is so small (+/-2V), it causes ripples in the magnitude of the AC voltage (Fig. 4 (b)) which is significantly reduced in case of variable DC voltage (Fig 5(b)).

VI. Conclusion

A new and simple technique for voltage and frequency control of self excited induction generator with variable DC link voltage was proposed. The voltage regulation is done by controlling the modulation index rather than the DC voltage. This technique was proved to be excellent for controlling voltage and frequency under sudden changes in load and speed. The technique could also compensate for reactive power demand of the inductive loads. Beside its simplicity, the technique eliminates the need for an auxiliary switch as a chopper in the DC side and this also eliminates the high switching current components in the DC capacitor which reduces its current rating and increases its lifetime. Simulation results have been given to validate the proposed technique as well as detailed design of the DC resistance.

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