Design and Control of Cost Effective Wireless Power Transfer Systems of AC Motor Drives with Efficiency Maximization

[1]Mr.T.Y. Saravanan

[1]Assistant Professor, Department of Electrical and Electronics Engineering, Narayana Engineering College, Gudur, AP, India,524 101

[2]V.Jaya Sindhu [3]T.Lahari[4]B.Vishnu Priya [5] K.Anusha

[2,3,4,5]UGStudents, Department of Electrical and Electronics Engineering, Narayana Engineering College, Gudur, AP, India,524 101

Abstract-**Motor drives supplied through wireless power transfer (WPT) systems require a high frequency inverter in primary side, a rectifier and low frequency inverter in secondary side of the system. Due to this arrangement, reliability and efficiency are reduced whereas the cost and complexity of the system are increased. In this paper, a single inverter in the primary side drives an induction motor by removing rectifier and inverter and replacing it with AC/AC chopper in the secondary side. In this way, the desirable ac power can be injected into the motor effectively and also the WPT system efficiency is improved because of reduced power conversions. The performance of proposed wireless ac motor drive under a closed-loop V/f control system is verified by simulation using MATLAB/SIMULINK.**

***KEYWORDS*-AC/AC converters, electric vehicles, wirelessmotordrives, wireless powertransfer.**

I. INTRODUCTION

Wireless Power Transfer(WPT)systems are increasingly designed for static and dynamic supply of future electric vehicles (EVs)[1, 2] and in-motion systems[1],[3]. Most of these systems are used for single-phase power transfer [4]. Inspite of the benefits of single-phase induction motors, especially adaptability to single-phasesupplies, their excessive winding current in high power applications and weak start-up torque had manufacturers not to employ the min conventional EVs, inclusively[5],[6].However, they may be used in small EVs by improving their start-up torque through a controlled switching capacitor [7]-[12]. Generally, in conventional wireless EV charging system with a cmotors,the dc supply is given to the primary side inverter, this ac power is first transferred to the secondary side of the system through loosely magnetic coupling. The power is then converted to dc by a passive rectifier in the secondary side of the system. Finally, the on-board driver converter (inverter) feed the motorby converting the dc power to the required ac one as shown in figure1[13].With the mentioned structure, the WPT system requires two converters with two compensators for power conversion from dc to ac in the primary side and ac to dc in the secondary sideas shown in figure1[16].Therefore, such system suffers from complexity andcost deficiency, in addition to reduced reliability and power transfer efficiency. Thus, eliminating compensator sand reducing power conversion stage together with the switching converter enhance system simplicity and cost effectiveness.

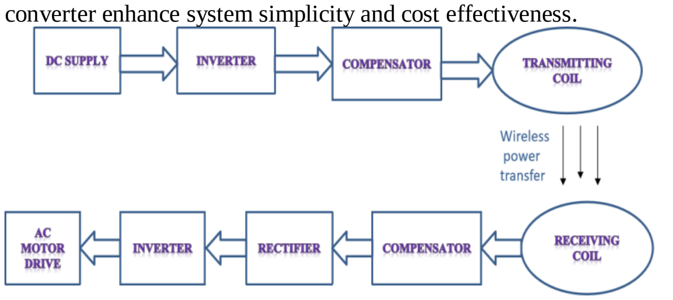

Figure1: Block diagram of AC Motor drives with two inverters using WPT system

The way to achieve the mentioned target sare different depends on the type of electric motor (EM) which are used inEVchargingapplications.Otherthanthesinglephaseinductionmotor,thedcmotorsandthree-phaseacmotors, especially switched reluctance motors are employed in small EVs with WPT charging systems.In[17],a three-phase switchedreluctance motor is supplied through a WPT system with three secondary windings that absorb the power at different resonant frequencies. In this method, an extra power conversion stage isemployed in the secondary side.Also, this process is applicable to multiple secondary side dc motors [18]. In addition,the wireless power transfer system is proposed to drive a secondary side servomotor[19]-[20].Inthissystem,theprimary inverter works under two different operating frequencies. As aresult, two distinct converters are employed in the secondaryside.Multireceiversarealsousedindependentlywithdifferent resonance frequencies to pick-up the primary injectedpower [21]-[23]. New compensator topologies are introducedin wireless motor drive applications to simplify the control procedure. A LCC compensator circuit is utilizedto remove the switching compensator and its control for multi-resonan tfrequency creation [24].

In this paper, the ac motor is supplied directly with a newwireless motor drive system is as shown in figure2. Here the ac power from primary side is transferred to secondary side via magnetic coupling.Usingan AC/AC chopper as a wave shaping converter in the secondary side of WPT system lead s to driving an induction motor from the primary side. The rectifier, inverter and the compensators are removed in this method. Due to this, the complexity and cost is reduced whereas the efficiency is increased due to less power conversion stages. A compatible control method is designed to drive the motor under constantV/F, which enhances the power quality delivered to the motor.

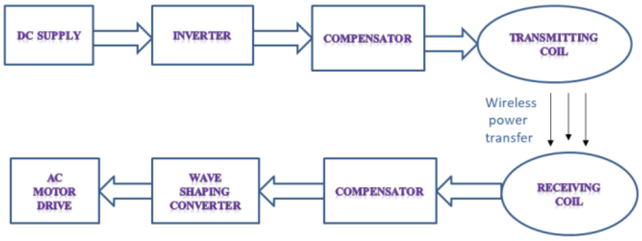

Figure:2 Block diagram of AC Motor drives with a single inverter using WPT system

II. SYSTEM CONFIGURATION AND MATHEMATICAL ANALYSIS

In the integrated system, the primary side inverter provides high frequency square wave voltage to transfer power through the loosely magnetic-coupling, with acceptable efficiency. Resonant converters are used in WPT systems to provide high-frequency current production, high efficiency of power transfer, and high power transfer capability. Fig.3 shows a WPT system including an inverter using S-PWM modulation together with the primary and secondary resonant circuit, and the magnetic link. High-frequency voltage across the inverter terminal, *Vinv*, can be realized in primary side. Accordingly, this results in high-frequency voltage and current at the output of primary side of the WPT system, *VL*. Fig. 3(a) includes the waveforms of *VL* and *Vinv*. It is seen that *VL* is a high frequency bipolar voltage. However, an electric motor, as a WPT system load, usually needs a sinusoidal lowfrequency voltage around its nominal frequency, as shown by *Vac* in Fig. 3(b). Therefore, *VL* should be converted to *Vac.* The available solution is to rectify *VL* to get a dc-link voltage and then convert the dc voltage to the lowfrequency sinusoidal voltage. This solution needs two extra power converters, a rectifier and an inverter.The entire wireless motor drive will be complicated and expensive. The main aim of this work is to provide an alternative solution for wireless motor drives with less complicated and cost.

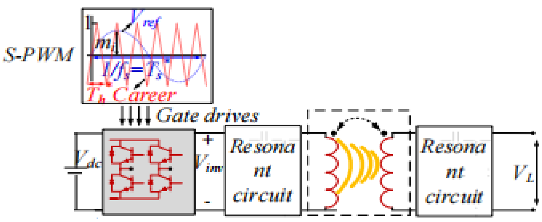

Fig3.WPT system analysis

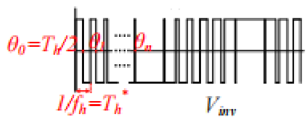

Figure 3(a):SPWM inverter output voltage

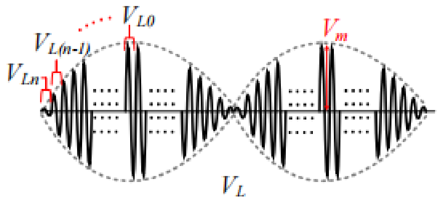

Figure 3(b): modulation voltage

A mathematical analysis is done in this section to tackle the presented problem analytically. The analysis is to convert mathematically *VL* towards the desirable voltage of the motor .The analysis requires a mathematical representation of *VL* in the first place [2]. The model consists of equivalent circuits of a series compensator at the primary and secondary side and an equivalent variable ac load (*RL*). The series-series compensator topology is sought here as it provides an optimum frequency of the system related to the maximum efficiency, independent from the output load [25]. The input to the model of Fig. 2(a) is the primary inverter voltage, *Vinv*. This is a PWM type square wave voltage as seen in Fig. 3(a). The square pulse is neither even nor odd symmetrical due to variable duty cycle based on the PWM modulation. By applying fourier transform to a square pulse of this voltage, the amplitudes of the 1st harmonic of *x th*voltage pulse can be evaluated for both even and odd parts as:

$$b_{1x} = V_{dc}\left(\frac{2-2\cos(2\pi f_h \theta_x)}{\pi}\right) \quad \text{-------(1)}$$

$$a_{1x} = V_{dc}\left(\frac{2\sin(2\pi f_h \theta_x)}{\pi}\right) \quad \text{----(2)}$$

Hence, the *x th*pulse voltage, *Vinv(x)*, can be calculated as:

$$V_{inv(x)} \cong a_{1x}\cos(2\pi f_h t) + b_{1x}\sin(2\pi f_h t) \text{--(3)}$$

Where,

$$\theta_x = \frac{1}{2f_h}\left(1 - m_i \sin{}^{\pi x}/_{2n}\right) \quad \text{---(4)}$$

$$\text{n} = \frac{f_h}{4f_s}, \quad \text{---(5)}$$

Here,

m_i isthe PWM modulation index
f_h is the switching frequency
f_s is the reference frequency
θ_x is the duty angle
V_{dc} is the dc supply voltage

By Considering natural oscillations, the general formula for $V_{inv}(t)$ can be obtained by adding each square pulse to form a pulse train as

$$V_{inv(1)}(t) = \sum_{k=0}^{\infty}[U(t-k\,T_h/2) - U(t(k+1)\,T_h/2)] \times \begin{pmatrix} \sum_{x=0}^{n} V_{Lx}\;.\;[U(t-xT_h) - U(t-(x+1)T_h)] \\ +\sum_{x=n-1}^{0} V_{Lx}\;.[U(t-xT_h-T_h/4) \\ -U(t-(x+1)T_h - T_h/4)] \end{pmatrix} - \quad --(6)$$

U(t) is defined as a step function. With some simplification, *Vinv(1)(t)* can be calculated as:

$$V_{inv(1)}(t) = 2\frac{V_{dc}}{\pi}\cos\left(\frac{\pi}{2}m_i\sin(2\pi f_s t)\right) .\sin\left(2\pi f_h t - \frac{\pi}{2}m_i\sin(2\pi f_s t)\right) \text{---(7)}$$

Considering *mi=1* and some simplification, eq(7) changes to

$$V_{inv(1),m_{i=1}}(t) = 2\frac{V_{dc}}{\pi}\sin\left(2\pi f_s t - \frac{\pi}{2}\sin(2\pi f_s t)\right).\mathrm{Cos}\left(\frac{\pi}{2}\sin(2\pi f_s t)\right) \text{---(8)}$$

To obtain the modulated voltage formulation,the RLC resonant circuit should be analyzed. Fig.3(c) represents the equivalent circuit of a WPT system with the secondary side, which is modeled as *RL* under the secondary resonant frequency.

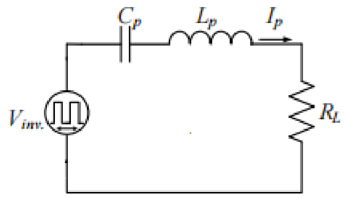

Figure3(c): compensation circuit

The resonant frequency of the primary and secondary sides are the same, i.e: Using the resonant circuit in both sides of the WPT system with resonance operating frequency as the 1st harmonic order According to Fig. 3(b), the modulated voltage *VL(t)*, under open-circuit condition can be calculated as:

$$V_L(t) = \frac{M.V_{inv(1)}}{C_s(R_1R_2+\omega_0^2M^2)} \text{----(9)}$$

Comparing (8) with low frequency voltage of motor, justifies two modifications (8) to provide a low frequency voltage to the motor. The first one is to convert the pulsating voltage waveform to a sinusoidal waveform. The other one is to filter the high frequency variations. These are done separately as follows. The first task is done if the low frequency variations in each half cycle are bounded between zero and a peak value. This can be achieved in an interval of *T=nTs+t* by:

$$V_{conv.} = \begin{Bmatrix} \frac{V_L+|V_L|}{2}, t \le \frac{T_s}{2} \\ \frac{V_L-|V_L|}{2},\ \frac{T_s}{2} \le t \le T_s \end{Bmatrix} \quad \text{---(10)}$$

The result is demonstrated in Fig.4. It is seen that the resulting waveform contains high frequency oscillations. Therefore, the second task should get rid of theses oscillations. This can be achieved by a simple low pass filter. Applying a large enough inductance (*Lf*) as a filter, the high frequency current as a result of high frequency variations will be omitted through passing this filter. The motor is modeled as variable *RL*. Therefore, the related transfer function of the filter is obtained as:

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$$|H(\omega)| = \frac{R_L}{\sqrt{R_L^2 + (\omega L_f)^2}}. \quad \text{-----(11)}$$

Here,

R_L is the load resistance

L_f is the filter inductance

No high frequency current can pass through the filter as *H(ω)* is insignificant in (11) at high frequencies.

III.CONTROL SYSTEM

In this system, the primary side inverter provides high frequency voltage to transfer power through loosely magnetic-coupling, with acceptable efficiency. The high frequency voltage is produced by a bi-polar PWM switching algorithm of the full-bridge inverter.It drives the electric motor with a closed-loop V/f controller. The sinusoidal reference voltage obtained from a *V/f* look-up table, is applied to the PWM switching algorithm. In the next step, the modulated high frequency voltage in the primary is demodulated by the AC/AC chopper in the secondary side and supplies the motor with a low frequency sinusoidal current. The AC/AC chopper topology with the injected current to the electric motor is demonstrated in Fig.4(a) with the modulated and demodulated voltage on both sides of the chopper. Two reversed switches are used in upper and lower sides of the chopper in order to control the current flow in both sides.Generally, in WPT systems, magnetic coupling only transfers the high frequency power. Whereas the electric motors are designed for a low frequency power.The AC/AC chopper converts the high-frequency voltage of the secondary winding produced by the primary inverter, and provides a proper voltage with a low frequency main harmonic according to the chopper switching states, two operating modes can be considered for the electric motor.

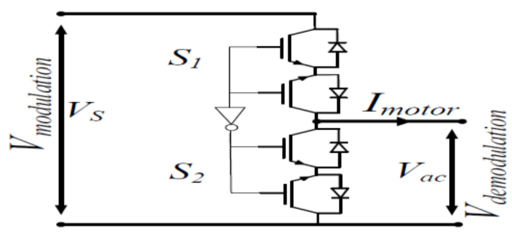

Figure4:AC/AC chopper Topology

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To perform the mentioned conversion, a bi-directional AC/AC chopper with a proper switching strategy isused here to convert, *VL*to *Vconv.*, according to (10). By thisway, a high frequency 1st- harmonic order of the voltage with low frequency variation (in the range of motorrating) is provided across them otorterminals. This simple technique removes the drawbacks in the conventional solution. In this arrangement, the ac power transferred to the secondary side is fed to the motor with out needing arectifier and an inverter. Instead, an AC/AC chopper as a simple self-controlled converter is used at the load side converts the high frequency voltage produced by the primary inverter, and provides a proper voltage with a low-frequency fundamental waveform.

The AC/AC chopper topology is demonstrated in Fig. 4. The chopper comprises two bi-directional switches. Each switch consists of two power electronic switches with the reverse diodes, where the emitters are connected to each other and can be driven via only a single gate driver. Since the motor current is low-frequency comparing to the high-frequency input wave, bi-directional switches are required to control the current flow in both negative and positive directions. According to the chopper switching states, two operating modes can be considered for the motor.

1) Power Mode

During this mode, the upper switches of the chopper leg, *S1*, turn on and the lower ones, *S2*, are off. Therefore, the motor is supplied by the WPT system via the pass mentioned by the solid line in Fig.4 (a), while the power recovers within the secondary side compensator (*CS*) via the path determined by the dashed line in Fig. 4(a).

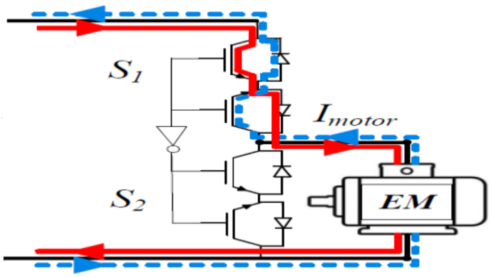

Fig 4(a):Power flow in power mode

2) Bypass Mode

During this mode, unlike the power mode, *S1* is off and *S2* is on. This provides the motor current to be circulated. Fig. 4(b) shows the bi-directional current flow through the AC/AC chopper switches in the bypass mode.

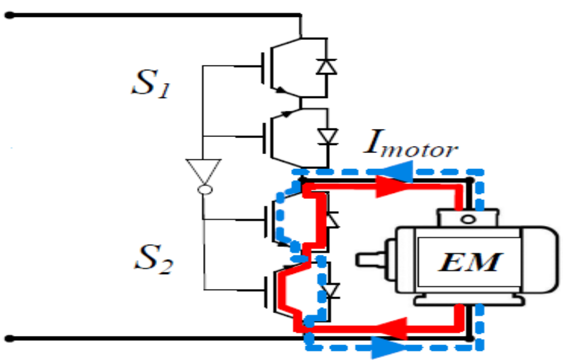

Fig 4(b):Power flow in bypass mode

IV. SIMULATION MODEL& RESULTS

A MATLAB/Simulink based simulation analysis of the proposed system is carried out in this section.The overall Simulink model of the integrated system is mentioned as shown in fig5(a).

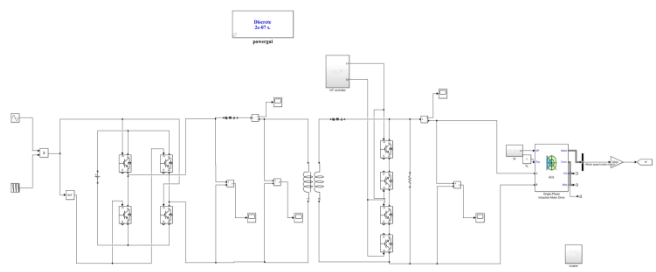

Fig5(a):overall Simulink model of the integrated system

In the proposed wireless motor-drive system, SPWM modulation technique is applied to the inverter which produces pulsating voltage .By connecting the series compensator, we get high frequency modulated voltage and current.This modulated voltage and current can be demodulated by adding simple AC/AC chopper.This low frequency voltage and current is given to the motor as input.

In the system secondary side, an AC/AC converter demodulates the voltage with a symmetrical switching. A block diagram of the secondary chopper switching is shown in Fig. 5(b).The closed-loop *V/f* control block diagram is applied to the motor drive system. In half period,S1 is turned on for positive voltage and off for negative one. For the second half period, S1 is turned off for positive voltage and on for negative. In the above modes, switches S2 turn on or turn off contrariwise the switches S1. By this way, the primary winding voltage is converted to a suitable low-frequency AC voltage across the electric motor. In this way, the secondary winding voltage, *Vmod*, is converted to a suitable low frequency AC voltage across the electric motor, *Vdem.*.

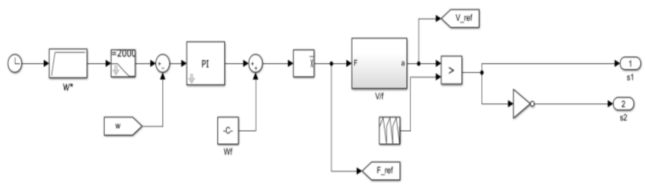

Fig.5(b):Schematic of the closed-loop V/f control system with the AC/AC chopper's switching algorithm.

In the fig.5(b) ,the reference speed is compared with the rotor speed with the comparator and the error is given to the PI controller. Angular frequency is added to the output of the PI controller.From this we get the reference frequency and that is given to the look up table from which we get the reference voltage.The reference voltage is compared with the carrier wave and that is used for switching of AC/AC chopper.

Table I present the motor and WPT system specifications, respectively. Using this WPT topology for direct wireless motor drives together with the proposed control system, the WPT system efficiency becomes higher comparing to the conventional wireless motor drive system

TABLE I
SYSTEM SPECIFICATIONS

symbol	Quantity	value
V_{dc}	DC voltage	220V
L_p	Primary self-inductance	$130\mu H$
L_S	Secondary self-inductance	$130\mu H$
C_p	Primary capacitance	121.5nF
C_s	Secondary capacitance	121.5nF
R_1	Primary resistance	0.3Ω
R_2	Secondary resistance	0.1Ω
f_h	WPT operating frequency	29KHZ-40KHZ
K	Coupling coefficient	0.05-0.1
p	Motor rated power	0.25hp
Vm	Motor operating voltage	40V-180V
f_s	Motor operating frequency	20HZ-50HZ

In this study, the optimum frequency is *fopt=40 kHz*. So, the voltage amplitude can be set by adjusting the operating frequency. Accordingly, the inverter modulation is based on bi-polar PWM with a unity modulation index and a triangular carrier frequency of 29 kHz-40 kHz during the motor start-up until the steady state where the reference motor speed and motor current frequency reach their maximum values.. Unlike the usual PWM modulation controlling the voltage by adjusting the modulation index, in this paper the modulation index is set at unity (*mi=1*) all the time. Instead, the voltage amplitude is controlled by adjusting the career frequency as the operating system frequency. Unlike the common drive systems providing a low frequency power to supply the motor, the resonant converter used in this study dispatch the high-frequency power toward the magnetic link. This is essential, because the magnetic link is only able to transfer high-frequency power to the secondary side. In addition, it is expressed above that the peak amplitude of the output load voltage, *Vm*, can be adjusted by setting the carrier frequency. For carrier frequency near the optimum one, the maximum amplitude can be provided.

V. SIMULATION RESULTS

In order to demonstrate the wireless motor drive system performance under the proposed control system, the simulation results are depicted. Fig.6(a) illustrates the pulsating voltage across the primary side inverter and fig.6(b) represents the modulated voltage and the converted voltage is obtained by the AC/AC chopper as well as the current injected to the motor (I_{motor}). In this situation, the frequency of the reference sinusoidal voltage associated with the PWM modulation is the same as the main harmonic voltage across the motor as well as the motor current. This frequency is defined as $f_s=1/T_s$. Fig. 6(c) represents the motor current in primary side.The converted voltage which is shown in fig.6(d) is applied to motor has the low-frequency harmonic content as the envelop voltage obtained by curving the peak amplitude of each V_{Lx}. Hence, the higher order current produced by V_{conv}.is removed. As a result, motor current like Fig. 6(e) is provided to feed the motor.

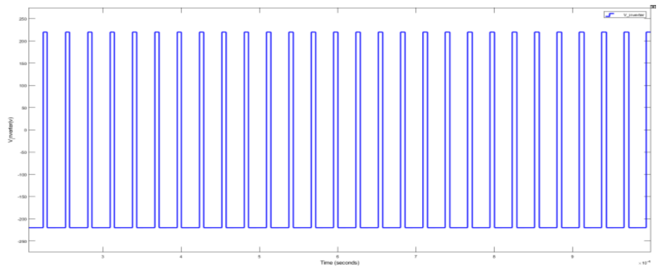

Fig 6(a):output voltage of primary side inverter

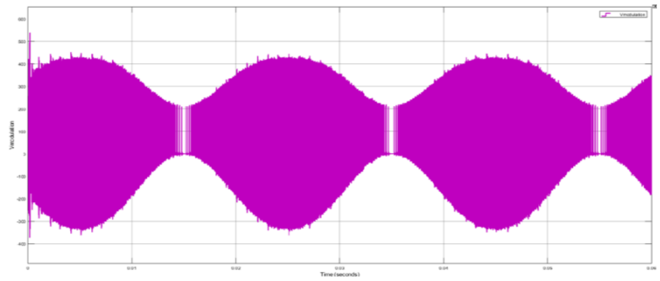

Fig 6(b):modulated voltage

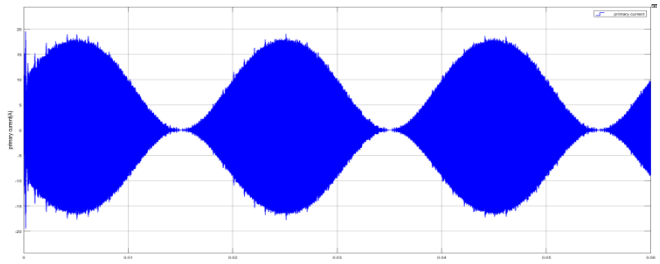

Fig 6(c):primary side current

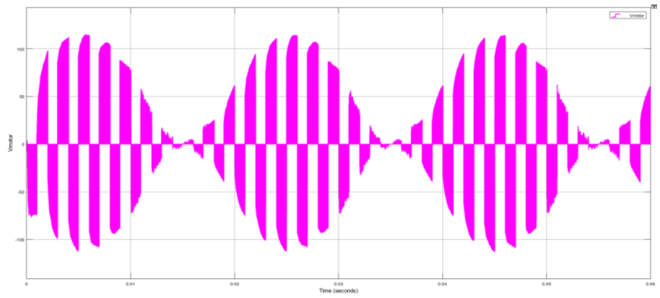

Fig 6(d):input voltage of motor

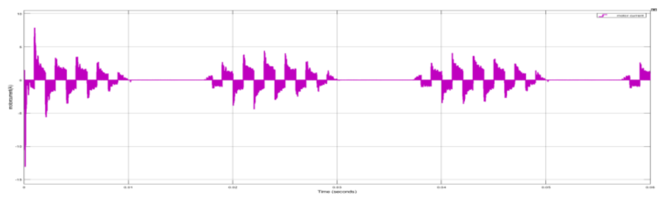

Fig 6(e):input current of motor

In this method, the speed of the motor is as shown in fig.6(f) and the specific working points of the voltage-frequency curve is tracked by the control system until the steady state conditions are reached as shown in fig.6(g).The reference PWM voltage is depicted in fig.6(h).

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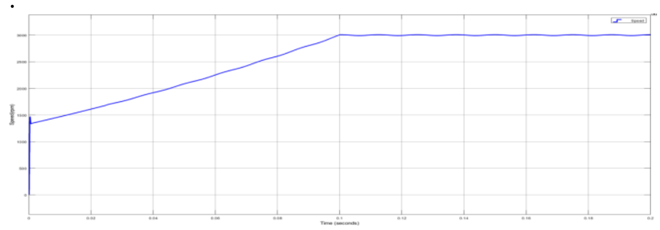

Fig 6(f):speed of motor

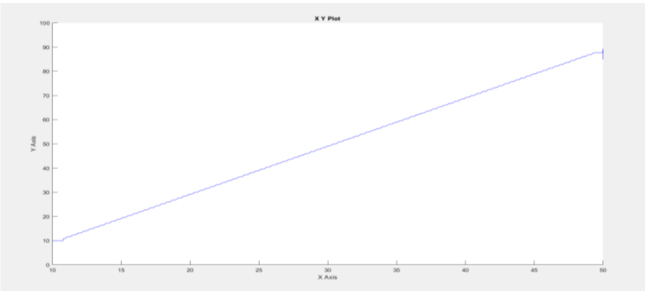

Fig 6(g):V/F curve

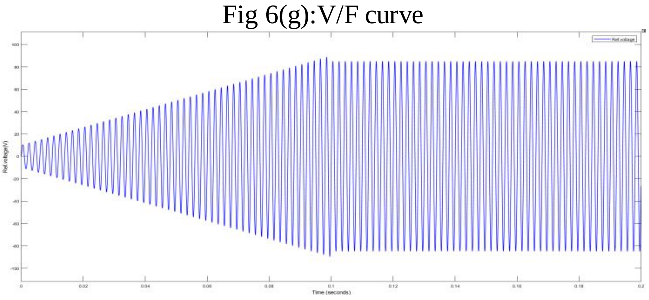

Fig 6(h):reference PWM voltage

The reference ramp frequency is applied to the control system. As it is found in Fig.6(h), the rotor frequency follows the reference one in both transient and steady state modes, properly. The starting value of the reference frequency is a little more than zero. This is considered for the initial value of the reference voltage, too. A PI controller is used to set the rotor frequency.

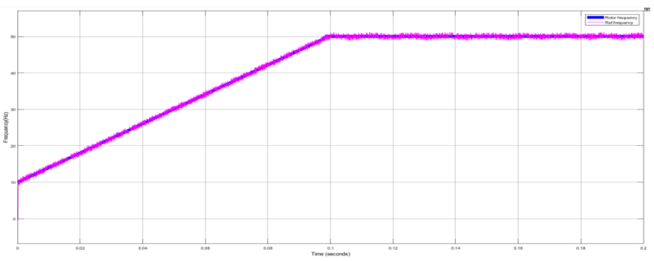

Fig 6(i):referencevs rotor frequency

VI. CONCLUSION

In this paper, a WPT system with a cost effective structure for supplying an induction motors is proposed. In this system, the EM can directly be fed by the WPT system. The system includes a primary side inverter provides high-frequency ac power to be transferred mainly through the loosely-coupled magnetic link with sufficient efficiency. This inverter also drives the electric motor under constant V/F control. A switching voltage converter is used in the secondary side of the WPT system to convert high-frequency voltage to low-frequency one, which is desirable for driving the motor. The converter is a simple AC/AC chopper. By using this system, the secondary side inverter which is commonly used in wireless electric motor drives, is eliminated. This leads to an improvement of WPT system efficiency in comparison with the conventional motor drive systems due to less power conversions. A compatible constant V/F control based on a non-resonant WPT system is also introduced that adjusts the fundamental voltage across the motor drive with desirable frequency. The simulation results show the effectiveness of the proposed system. It is applicable to wireless moving systems like dynamic wireless charging of electric vehicles.

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