Fuzzy logic based Single-Stage Three-Phase AC-AC Converter for Inductive Power TransferSystems

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Abstract

In this paper proposed fuzzy logic based three-phase ac-ac matrix converter for inductive power transfer (IPT) systems with soft-switching operation and bidirectional power flow . The proposed converter can generate high-frequency current directly from a three-phase ac power source without a dc link. Unlike conventional ac-ac converters, the converter can provide a high frequency current without any current sag around ac source zerocrossings for IPT systems. The proposed topology is expected to have high reliability and extended lifetime due to the softswitching operation and elimination of short life electrolytic capacitors. Soft-switching operation will also reduce switching stress, switching losses, and electromagnetic interference (EMI) of the converter. A simple control strategy based on energy injection and free oscillation technique is used as the control method. Theconverter is comprised only seven switches, which in turn increase the reliability, efficiency and reduce cost. The converter operates in eight modes, which are described in detail. In this paper, the compensation scheme of leakage inductance and the coil windings parameters are first analyzed and evaluated; then, the genetic algorithm is used for optimizing the parameters of a fuzzy controller in order to achieve the feedback power control for the proposed control strategy. The simulation results show the effectiveness and superiority of the proposed power control method.

Index Terms—AC-AC converter, inductive power transfer, matrix converter, soft switching

I. INTRODUCTION

Inductive power transfer (IPT) systems are emerging technology for transferring electric power to a variety of applications without any physical contacts [1]. This technology transfers power from one system to another across a large air gap and through a loosely coupled inductive link. It offers high efficiency typically between 85-90%, robustness, and high reliability, even when used in hazardous environments, as it is unaffected by dust or chemicals and eliminates sparking and the risk of electrical shocks [2],[3]. Therefore, it is a safe, robust and clean way of transferring power and has rapidly gained increased interest in the commercial and industrial applications. The IPT technology has been successfully employed in many applications, including systems for materials handling [1], biomedical implants and transportation systems [4],[5]. Especially this innovative technology can be used for static and dynamic wireless power transfer for electric vehicles (EVs) [2],[6].

In a loosely coupled IPT system due to weak coupling of the coils the inductive link requires a strong magnetic field to be created to deliver high power levels at large air gaps. To achieve this, it requires the use of power converters that can generate large currents at high frequencies often in the kilohertz ranges. In order to generate a high-frequency current on the primary side, specific power converters are employed in IPT systems. Power converters play a key role in the performance of the IPT systems. Recent developments in IPT systems have heightened the need for high power reliable and efficient converters. Normally, these converters take 50/60 Hz mains and convert to high-frequency using an ac-dc-ac two-stage power conversion. A typical configuration of an IPT system is shown in Fig. 1. The power source of an IPT system is usually the electric utility (single-phase or threephase) supplying power at 50/60 Hz. Voltage-source inverters (VSI) based on pulsewidth modulation (PWM) with a front-end rectifier have become the preferred choice for most practical applications [7]. This is mainly due to its simple topology and low cost. On the other hand, this two-stage topology has low-frequency harmonics on the dc link and the ac input line, which requires the use of very bulky short-life electrolytic capacitors for the dc link and a large low-pass filter at the output [7]. Several topologies have been proposed to solve the problems of the traditional ac-dc-ac power converters,[8]-[10]. The main alternatives for two-stage converters that can convert energy directly from an ac source to a load with different frequency and amplitude without any energy storage elements [11]. These converters have the advantages of the simple and compact topology, bidirectional power flow capability, high-quality input-current waveforms, and adjustable input power factor independent of the load [11],[12]. Particularly different converter typologies have been proposed for IPT applications [13]-[18]. A simple, compact and highly efficient single-phase matrix converter for IPT applications is presented in [13]. The energy injection and free oscillation control strategy is applied to the topology. However this matrix converter suffers from current sags around input ac voltage zero-crossings. In this paper, a new three-phase ac-ac matrix converter for IPT systems is proposed. The proposed matrix topology is composed of seven switches which six of them are reverse blocking switches and one is regular switch. A variable frequency control strategy of the converter is based on energy injection and free oscillation technique.

II. Inductive power transfer

More recently applications for IPT have spread to the automotive industries where in the push for electrification of personal transportation systems IPT can offer some highly attractive possibilities . These are hands-free charging systems that are unaffected by dirt, chemicals, or the weather and can, in principle, be extended to dynamic charging systems where a vehicle may be charged while it is in motion on an instrumented lane along the road Such systems offer convenience and reliability and surprisingly may well be the lowest cost of all private transportation options including conventional vehicles. But in achieving these features there are some significant difficulties that must be overcome.

inductive coupling WPT

According to Oersted's law, a steady current produces a magnetic field around it [14,140]. Furthermore, BiotSavart law describes the relation between the magnetic field and magnitude, direction, proximity and length of the electric current by which it was generated:

$$B = \frac{\mu_0}{4\pi}\int_l \frac{Idl \times e_r}{r^2}$$

The magnetic field generated by TX circular coil at the point x (at RX coil) would then be:

$$B = \frac{\mu_0 N I a^2}{2(a^2+d^2)^{3/2}}$$

where N is the number of wire loops, I is the transmitter inductor current, a is the radius of the TX coil, d is the distance between TX and RX .

The magnetic flux passing through the receiver will be expressed as:

$$\phi = \iint_s B \, dS$$

where B is the magnetic flux density generated by the transmitter and S is the area of the receiver coil surface [9.19]. Since the time-dependent current of the transmitter coil produces magnetic flux variation in the receiver coil, electromotive force (EMF) is induced in the RX coil, which we can derive by applying Faraday's law

$$\varepsilon = -\frac{d\phi}{dt}$$

Secondary coil whose magnetic field is opposing the time variation in the magnetic flux according to Lenz's law. Hence, the power is transferred from TX coil to RX coil.Self-inductance is the property of the circuit when its own magnetic field is opposing the current change in the circuit. Self-inductance of the coil can be defined as:

$$L = \frac{N\phi}{I}$$

$$\varepsilon = -L\frac{dI}{dt}$$

or

$$\varepsilon = -M\frac{dI}{dt}$$

Obviously, the EMF induced on the coil is directly proportional to the self-inductance/mutual inductance of the coils and rate at which the current is changing. Another representation of mutual inductance is the following:

$$M = k\sqrt{L_1 L_2}$$

The coupling factor defines the grade of the coupling, i.e. how much flux of the total flux actually penetrated the receiver coil. It can have a value from 0 to 1 (from zero to perfect cou-pling).

According to (2) and (3) and if the current is alternating, we retrieve:

$$\phi = \iint_A \frac{\mu_{0Ni\sin(\omega t)a^2}}{2(a^2+d^2)^{3/2}} dA$$

and combining with (4):

$$\varepsilon = -\frac{d\left(\iint_A \frac{\mu_{0Ni\sin(\omega t)a^2}}{2(a^2+d^2)^{3/2}} dA\right)}{dt}$$

or

$$\varepsilon = -\mu_{0Ni\omega\cos(\omega t)} \iint_A \frac{a^2}{2(a^2+d^2)^{3/2}} dA$$

Which explains that the voltage induced to the secondary coil depends on the current/voltage in the primary coil, the frequency of the current/voltage in the primary coil, the distance between the coils and the surface area of the coils. The resulting two coil coupling system is depicted in Figure 5.

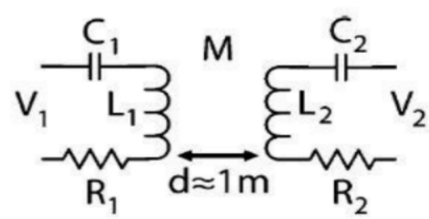


Figure 1. Simplified representation of the two coil coupling system.

Here C_1 and C_2 are tuning capacitors, L_1 and L_2 are coupled inductors with mutual inductance M, R_1 and R_2 represent parasitic resistances (loss resistances in the inductors), d is the distance between the coils and V_1 and V_2 are input and output voltages. the output power of the second coil can be defined as:

$$P_{out} = \frac{{V_1}^2\omega^2M^2R_L}{(R_1(R_2+R_L)+\omega^2M^2)^2}$$

$$\eta = \frac{\omega^2 M^2 R_L}{R_1 (R_2 + R_L)^2 + \omega^2 M^2 (R_2 + R_L)}$$

Where the transmission efficiency η is defined as a ratio of input to output power. Thus the overall efficiency of the system depends only on the transmission frequency, mutual inductance, coils' parasitic resistances and load resistance. Q factor (Quality factor) is defined by the ratio of the inductance to the resistance of the coil. A higher Q factor means a lower energy loss and so better transmission efficiency. Usually Q factor has values from 0 up to 1000 for WPT coils.

$$Q = \frac{\omega L}{R}$$

Obviously, Q factor increases when the operating frequency increases. However, when it reaches its peak values, it will decrease as the operating frequency continues to rise. What is more, a higher Q factor means a narrower band-width, which results in dropped coupling efficiency and the need of a tuning circuit. Now the maximum transfer efficiency is defined

$$\eta = \frac{k^2 Q_1 Q_2}{(1 + \sqrt{1 + k^2 Q_1 Q_2})^2}$$

Consequently, in order to reach the maximum efficiency, developers should optimize the coupling and quality factors of their systems.

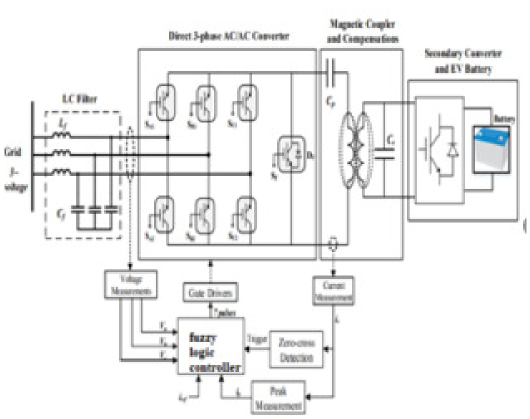


Fig. 2. The IPT model and its components simulated in MATLAB/SIMULINK.

III. THREE-PHASE AC-AC CONVERTER

Proposed three-phase ac-ac matrix converter. one regular switch (IGBT/MOSFET) which is in parallel with the resonant tank. In this figure, Cp represents the primary compensation capacitor, Lp is the primary self inductance and Req is the reflected resistance of the load at the secondary to the primary circuit. In [2], a control strategy for a single phase ac-ac converter based on energy injection and free oscillation of the resonant circuit is presented. This control method is further developed in this paper and is applied to the proposed three-phase converter.

The operation of the converter can be described in eight modes which are presented in Table I. Each mode takes place only in one half cycle of the output current. Modes 1 to 6 are energy injection modes and modes 7 and 8 are free oscillation modes. In mode 1 to 6, the resonant current (ir) is positive the absolute value of the previous peak current (ip) is lower than the reference current (Ir) and therefore energy should be injected to the LC tank for a half cycle to increase the current and the output is switched between the most positive and the most negative input lines and the energy is injected into the LC tank for a half cycle of the output resonant current. The switching is performed based on the measured input voltages according to Table I and using six switches, SA1,SA2, SB1, SB2, SC1 and SC2 which are used to switch the three-phase input lines to the output during modes 1 to 6. Mode 7, occurs when the previous peak current (ip) is positive and is higher than the reference current (Ir) and therefore energy injection to the LC tank should be avoided

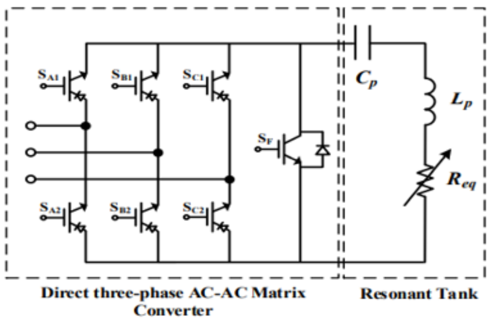


Fig. 3 Proposed three-phase ac-ac matrix converter.

TABLE I
SWITCH STATES IN DIFFERENT MODES OF OPERATION.

Mode	Resonant Current	Input Voltages	On Switches
1	$\lvert i_p \rvert < I_r, i_r > 0$	$V_c < V_b < V_a$	S_{A1}, S_{C2}
2	$\lvert i_p \rvert < I_r, i_r > 0$	$V_b < V_c < V_a$	S_{A1}, S_{B2}
3	$\lvert i_p \rvert < I_r, i_r > 0$	$V_c < V_a < V_b$	S_{B1}, S_{C2}
4	$\lvert i_p \rvert < I_r, i_r > 0$	$V_a < V_c < V_b$	S_{B1}, S_{A2}
5	$\lvert i_p \rvert < I_r, i_r > 0$	$V_b < V_a < V_c$	S_{C1}, S_{B2}
6	$\lvert i_p \rvert < I_r, i_r > 0$	$V_a < V_b < V_c$	S_{C1}, S_{A2}
7	$\lvert i_p \rvert > I_r, i_r > 0$	–	D_F
8	$i_l < 0$	–	S_F

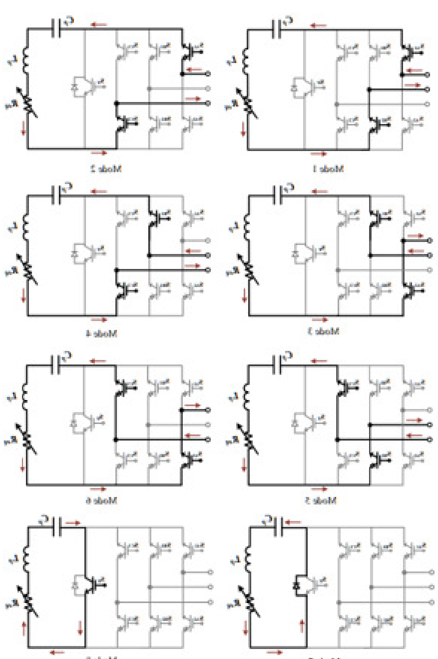


Fig. 4. The current path in the proposed converter in eight modes of operation.

for a half cycle to decrease the current. In this mode, the LC tank goes in a free oscillation state and the resonant current is positive which is conducted through the intrinsic body diode (DF) of the parallel switch (SF) as shown in Fig. 4 for mode 7. In mode 8, the resonant current is negative and the switch SF is on. Since the resonant current becomes negative after any mode from 1 to 7, mode 8 always occurs after any other mode of operation. The output current of the proposed converter is regulated around the reference current by alternating the state of the converter between energy injection and free oscillation modes.

In Fig. 3, a conceptual plot of three-phase input voltages, resonant current and corresponding switching signals of the converter in different modes of operations are presented. Also, Fig. 4 demonstrates the resonant current path in the proposed converter, in 8 modes of operation. Based on these figures it can be seen that the SF is repeatedly switching the circuit to the free oscillation mode (mode 8) with a negative current and DF turns on whenever the resonant current is positive and the circuit should go into free oscillation mode.

IV. FUZZY LOGIC CONTROLLER

Fuzzy logic is applied with great success in various control application. Almost all the consumer products have fuzzy control. Some of the examples include controlling your room temperature with the help of air-conditioner, anti-braking system used in vehicles, control on traffic lights, washing machines, large economic systems, etc.

A control system is an arrangement of physical components designed to alter another physical system so that this system exhibits certain desired characteristics. Following are some reasons of using Fuzzy Logic in Control Systems

- While applying traditional control, one needs to know about the model and the objective function formulated in precise terms. This makes it very difficult to apply in many cases.

- By applying fuzzy logic for control we can utilize the human expertise and experience for designing a controller.
- The fuzzy control rules, basically the IF-THEN rules, can be best utilized in designing a controller.

Followings are the major components of the FLC as shown in the above figure –

Fuzzifier – the role of fuzzifier is to convert the crisp input values into fuzzy values.

Fuzzy Knowledge Base – It stores the knowledge about all the input-output fuzzy relationships. It also has the membership function which defines the input variables to the fuzzy rule base and the output variables to the plant under control.

Fuzzy Rule Base – It stores the knowledge about the operation of the process of domain.

Inference Engine – It acts as a kernel of any FLC. Basically it simulates human decisions by performing approximate reasoning.

Defuzzifier – the role of defuzzifier is to convert the fuzzy values into crisp values getting from fuzzy inference engine.

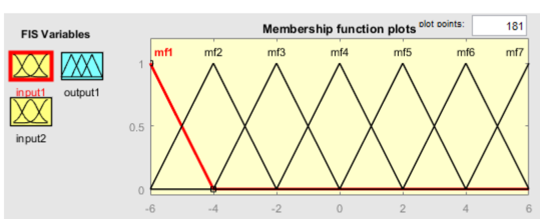


Fig.5Shows the Membership functions for error.

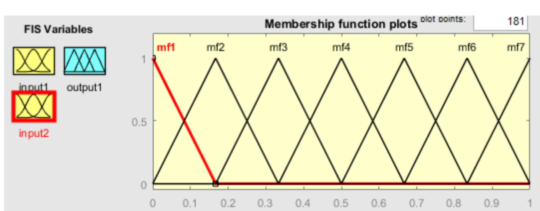


Fig.6 Shows the Membership function for Differentiated-error.

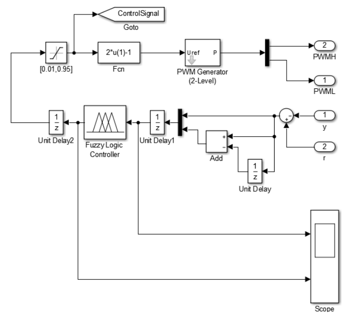


FIG 7: Simulink model of proposed system

V. simulation results

The proposed three-phase converter which is presented in Fig. 2 is simulated using MATLAB/SIMULINK. The IPT model is shown in Fig. 5. This model is comprised a threephase main grid with LC filter, the proposed three-phase ac-ac primary converter, primary and secondary magnetic structures with compensations capacitors and secondary load which is a battery charger for an electric vehicle. The controller of the primary converter and its components are also shown in Fig. 5. The measurements include three-phase input voltage and output resonant current of the LC tank. The controller is triggered in each zero-cross of the resonant current and based on the voltage and current measurements the switching state of the of the converter is determined.

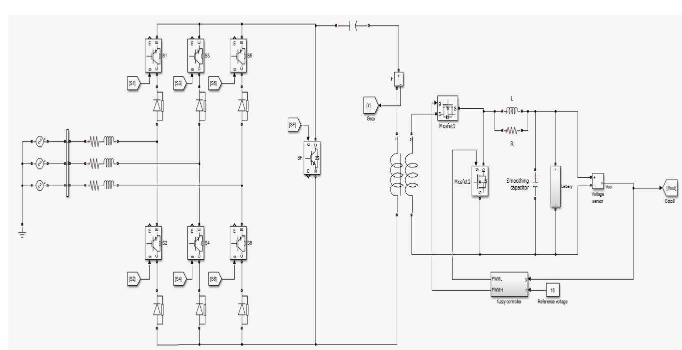
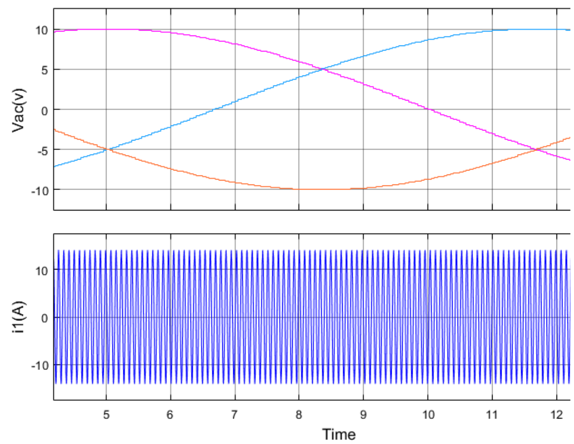
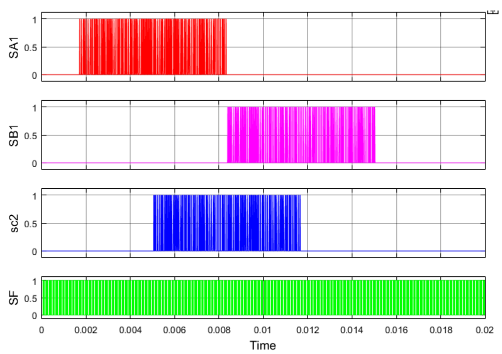


FIG 8: Simulink model of proposed system





The simulation results are shown in Fig. 9. This figure shows the three-phase input voltages and corresponding modes of operation, resonant current of the LC tank and switching signals of the SA1, SB1, SC2 and SF

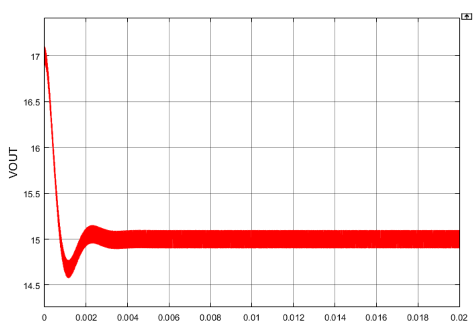
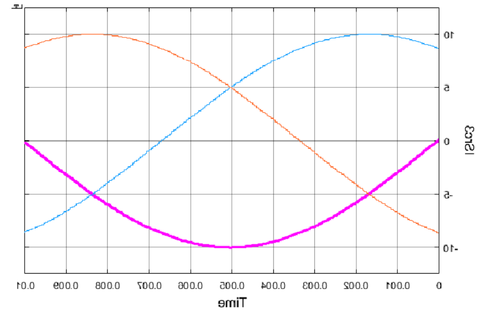


Fig 10: wave form of output voltage



(a)iscr2 response

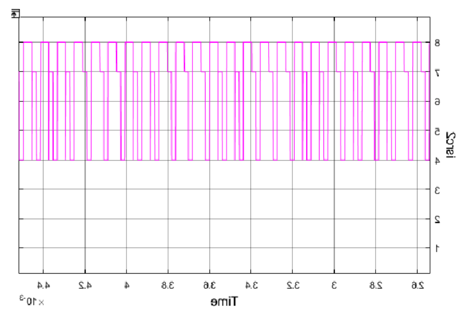


FIG 11: wave form of resonance current iscr3 response

CONCLUSION

This paper has introduced fuzzy logic based three-phase single-stage ac-ac converter for inductive power transfer (IPT) systems with zerocurrent switching and bidirectional power flow capability. The simulations results show that the proposed converter can generate regulated high-frequency current for IPT applications directly from a three-phase ac power source without a dc link with only seven switches. This paper has introduced the inductive power transferring system which has reduced the conversional stages by using three phase ac-acconverter. Because of this converter voltage, resonant current, and power can be controlled as well as. So this power transferring method is simple, user defined and effective method to transfer the power one device to another device.Whereas on the other hand Fuzzy controllers are able to handle the system efficiently and thereby improving the performance of the system and saves development time and costs.

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