A Novel Fuzzy based Phase Angle Estimation Scheme for Grid Connected Bidirectional Contactless Power Transfer System suitable for EVs and PHEVs

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Abstract—This paper presents a fuzzy based synchronization scheme for grid connected three phase Bidirectional Contactless Power Transfer (BCPT) system suitable for Electric Vehicle and Plug-in-Hybrid Electric Vehicle. The proposed synchronization scheme estimates the phase angle directly by tracking the grid voltage and frequency variations and facilitates synchronization of BCPT system with grid for charging and discharging operations. The entire BCPT system together with the synchronization scheme and its associated controllers is designed for a maximum power handling capacity of 2kW. The verification of design is done using simulations.

Index Terms— Bidirectional contactless power transfer, contactless coil, electric vehicles, fuzzy logic control, grid-to-vehicle, vehicle-to-grid and synchronization.

I. INTRODUCTION

Research on Bidirectional Contactless Power Transfer (BCPT) system has been increased significantly and is gaining more popularity as an accepted technology in application such as Electric Vehicle (EV) and Plug-in Hybrid Electric Vehicles (PHEV). BCPT system is a well proven technology and supports the fast charging of EVs, which is already been reported in literatures [1]–[4]. It overcomes the drawbacks of traditional wired charging system such as heating of the sockets and cables; risk of fire and electrical injuries; cable breakage etc [5]–[8]. A possible drawback of BCPT systems is the requirement of additional converters on either side of contactless coils, since the coils must be fed from a high frequency voltage source. However, recent advancements in resonant converters and simple controllers, desolates this problem and provides an effective solution for the problems of conventional systems [8]–[10]. One important part of the BCPT system is the grid synchronization unit [4]. Synchronization unit plays an important role in providing a synchronized reference phase signal between the charging station and the utility grid.

Various synchronization schemes and phase angle detecting techniques of grid have already been developed and reported in the literatures for different applications [11]–[18]. Among these techniques, the solutions using phase-locked-loop (PLL) is the state-of-the-art techniques in detecting phase angle of the grid voltage [11], [12], [14]. In [11], [15], [18] two synchronization schemes are presented using PI controller for distorted utility conditions and non-linear dynamic systems. However, these are not suitable for BCPT systems, as EVs’ batteries have different nominal voltages, Ampere-hour (Ah) ratings and varying State-of-Charge (SOC) levels. The uncertain behavior of EVs causes the PI regulator response to be too sluggish. Moreover, the realization of entire BCPT system synchronized with grid has rarely been reported. Therefore, there is a need for developing a complete BCPT system and the associated controllers with its synchronization unit by regulating the charging and discharging of EVs with different types of EVs’ batteries.

As a solution to overcome the shortcomings, this article describes a complete BCPT system with its synchronization unit, which estimates the phase angle directly by tracking the grid voltage and frequency variations while transferring power on both sides. The main building block of the proposed synchronization unit has an extended fuzzy based Phase Locked Loop system which operates well in nonlinear and uncertain situations. Another salient feature of the proposed BCPT system is the usage of dc-dc interface to regulate the EVs’ batteries of different ratings such as terminal voltages, Ah and SOC levels. Application of Fuzzy Logic Controllers (FLC) for converters in BCPT systems is found to be flexible enough to handle EVs’ batteries of different ratings.

The proposed synchronization scheme is tested by simulation, in a designed BCPT model interfaced with a single node of the real time grid scenario of a typical distribution system of Guwahati city [19] for a power handling capacity of 2kW. However, the system can also be designed for higher power rating with multi-charging points for charging a large fleet of EVs [1].

In detail the paper is organized as follows. Section II, III explains the basic building blocks of BCPT systems with its controller descriptions. Section IV describes the proposed fuzzy based synchronization schemes. Section V and VI reports the simulation results and conclusion.

II. BCPT BACKGROUND

A. Structure of BCPT system

Fig. 1 shows the schematic block diagram of a typical BCPT system with the synchronization unit. The BCPT system is comprises of two sides. The primary side is the charging station, which has a bidirectional three-phase ac-dc-ac converter to generate high frequency ac current in the primary side of contactless coil [5]. This side is magnetically
coupled to the vehicle system (secondary side), which has a bidirectional single-phase converter and a Buck-Boost (BB) converter connected with EVs’ batteries. As the EVs’ batteries have different nominal voltages, Ah ratings and SOC levels, dc-dc interface is essentially required for this purpose for regulating the battery voltages [2].

During charging operation, the EVs’ batteries are charged from the grid and during discharging operation, the EVs’ batteries supplies power to the grid. This process is described as Grid to Vehicle (G2V) and Vehicle to Grid (V2G) operations.

B. Modeling of BCPT system

The design process of BCPT system requires the determination of number of electrical parameters such as frequency, voltage, current, power etc in primary and secondary side. Considering these factors a brief design procedure has been reported in literature [2]. Rectangular coil topology is chosen for contactless coil, since it has better tolerance for misalignments [2]. The self and mutual inductances are calculated using Neumann’s formula. To achieve maximum power transfer; compensation capacitors (C1 and C2) are required on either side of the contactless coils. Series-series compensation is chosen here, as the primary capacitance is independent of either the magnetic coupling or the load [5].

III. CONTROLLER DESCRIPTIONS OF BCPT SYSTEM

As explained in the previous section, BCPT system transfers power in both the direction. The controllers used inside the system controls the switches of the converters and achieves bidirectional power flow functionality. The following section below describes the controller involved to perform these operations.

A. G2V Controllers

During charging operation, the primary side three phase converter converts three-phase ac voltage to dc voltage and then the dc is converted to high frequency ac. The high frequency current in the primary side of contactless coil is controlled by Energy Injection Control (EIC) [20] by sensing the primary side current (I_p). In the secondary side of contactless coil, the high frequency ac voltage is converted to dc voltage using diodes. Apart from this, a charging current controller using FLC-1 is used in the BB converter [21]. The reference current (I_ref) for charging the battery is controlled using battery voltage (V_batt) and reference power (P_ref). Then

- the measured current (I_mon) and reference current (I_ref) is compared and Error (E_r) and Error rate (ΔE_r) is given a input to FLC-1, which generates the required pulse for the BB converter to regulate the charging current of the battery.

- The controllers used in G2V operation for charging the EVS batteries are shown in Fig. 2.

B. V2G Controllers

In V2G operation, the power is transferred from the EV battery to support the grid. In order to maintain the grid side voltage constant, the voltage is sensed (V_mon) and compared with reference voltage (V_ref) of 650V. This is achieved by the dc link voltage controller in the BB converter.

Fig. 2: Block diagram of load voltage controller for G2V.

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Fig. 3: Block diagram of voltage controller for V2G operation.

- the measured current (I_mon) and reference current (I_ref) is compared and Error (E_r) and Error rate (ΔE_r) is given a input to FLC-2, based on the error duty cycle (D) is produced which is compared with the carrier signal of 25kHz and pulses are generated for BB converter as shown in Fig. 3. Apart from the DC link voltage controller, Sinusoidal Pulse Width Modulation (SPWM) technique is used for the inverter in EV battery system and charging station at a modest frequency of 4kHz, for dc to ac conversion, while supplying power to the grid. Besides, a synchronization controller also required for synchronizing the BCPT system during V2G operation. The pattern of fuzzy membership functions for FLC-1 and FLC-2 are shown in Fig. 4. The fuzzy rule base for FLC-1 and FLC-2 are given in Table I.

Fig. 4: FLC-1 and FLC-2 structure (a) Input: E_r and ΔE_r (b) Output: Duty cycle (D).

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TABLE I: Rule base for FLC-1 and FLC-2 controller

<table>
<thead>
<tr>
<th>E, ΔE,</th>
<th>NB</th>
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IV. FUZZY BASED SYNCHRONIZATION SCHEME

EVs’ batteries are connected to the utility grid through three phase converters present in the BCPT system. These power converters must be properly synchronized with the grid to obtain a very good performance. The phenomenon of synchronization can be achieved, when the BCPT system matches the utility grids; voltage, phase angle and frequency. This section covers the details about the proposed fuzzy based phase angle estimation scheme. The building block of the proposed scheme, mathematical model and power flow concepts are described.

A. Synchronization with Grid Voltage

Fig. 5. shows the descriptions of the fuzzy based synchronization scheme. Basically the scheme has three-stage structure. The proposed scheme tracks the voltage and frequency variations of the grid with respect to the inverter and produce the required phase delay for synchronization process. The first structure is composed of a discrete three phase PLL system with abc to d-qo transformation, which senses the grid voltage and estimates the frequency and amplitude. This block is cascaded with the second structure which is a power estimator block, which senses the inverter voltage and current as input. Based on the measured information, the power is calculated. The calculated power \(P_{meas}\) is given as input to the third structure. This structure has a fuzzy based phase angle controller (FLC-3). Here, in this stage the \(P_{meas}\) is compared with the reference power \(P_{ref}\). The error signal is obtained, which is given as input to FLC-3, which gives the required phase angle \(\delta\). From the \(\delta\) obtained, three phase symmetrical components are extracted. However, the three phase signals have a common frequency; there is no need to estimate the frequency of each phase independently. Based on the information obtained, the three phase reference voltages are generated and pulses are produced using SPWM technique. SPWM technique is used for obtaining better quality sine wave output for synchronizing with the grid [22]. The pattern of FLC-3 and its membership function with rule bases used for FLC-3 is shown in Fig. 6 and Table II.

![Fig. 6: FLC-3 structure (a) Input: \(E_i\) and \(\Delta E_i\) (b) Output: Phase angle \(\delta\).](image)

TABLE II: Rule base for synchronization (FLC-3) controller

<table>
<thead>
<tr>
<th>E, ΔE,</th>
<th>NB</th>
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<th>L</th>
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</table>

B. dq0 Modeling

The proposed fuzzy based synchronization scheme senses the grid voltage directly and tracks the voltage and frequency variations of the utility grid. The three phase utility voltage can be represented by Eqn. (1).

\[
V_{grid} = V_{abc} = \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \end{bmatrix}^T
\]

where,

\[
V_{abc} = [V_{an} V_{bn} V_{cn}]^T
\]

Under this assumption, the balanced voltage Eqn. (1) can be transformed to the d-q axis frame as given in Eqn. (3).

\[
V_{qdo} = T_s V_{abc}
\]

where, \(T_s\) is the transform matrix and is given by Eqn. (4).

\[
T_s = \frac{2}{3} \begin{bmatrix} \sin(\omega t + \frac{\pi}{6}) & \sin(\omega t - \frac{\pi}{6}) & \sin(\omega t - \frac{\pi}{3}) \\ \cos(\omega t + \frac{\pi}{6}) & \cos(\omega t - \frac{\pi}{6}) & \cos(\omega t - \frac{\pi}{3}) \end{bmatrix}
\]

Thus, \(V_{qdo}\) is obtained from three phase grid voltage. The frequency of each phase is extracted from the grid voltage and this will be same for all the three phases. In the next stage, the power is calculated from the inverter voltage and current and it is given as input to FLC-3. Further FLC-3, decides the phase angle \(\delta\) and based on that the reference three phase voltages are obtained by Eqn. (5).

\[
v_{abc} = T_m V_{qdo}
\]

where, \(T_m\) denotes the inverse transformation matrix and is given by Eqn. (6).

\[
T_m = \frac{2}{3} \begin{bmatrix} \sin(\omega t + \frac{\pi}{6} - \delta) & \cos(\omega t + \frac{\pi}{6} - \delta) & 1 \\ \sin(\omega t - \frac{\pi}{6} - \delta) & \cos(\omega t - \frac{\pi}{6} - \delta) & 1 \\ \sin(\omega t + \frac{\pi}{3} - \delta) & \cos(\omega t + \frac{\pi}{3} - \delta) & 1 \end{bmatrix}
\]

The modified transformation matrix given in Eqn. (6) has incorporated the transformer winding phase shift \(\frac{\pi}{6}\) and \(\delta\). Thus Eqn. (5) represents the reference voltage by considering the variations with respect to grid and BCCS unit.

C. Real Power Control

The power flow analysis in the proposed scheme is explained using a simplified equivalent circuit and phasor diagram shown in Fig. 7, in which the reactor \(X_L\) represents the complete filter and transformer inductance [22]. The real power control is achieved through the variation of phase angle difference between grid voltage \(V_{grid}\) and inverter voltage \(V_{inv}\). The power flow from G2V happens as long as \(V_{grid}\) leads \(V_{inv}\) and V2G occur, when the \(V_{inv}\) leads \(V_{grid}\). In Fig. 7, the phasor diagram shows \(V_{grid}\) leads \(V_{inv}\) at an angle \(\delta\), there will be a real power flow from grid to the inverter.

Thus, with the available charging infrastructure both V2G and G2V operations are possible. To achieve this power transfer the inverter voltage should be controlled by varying the phase angle \(\delta\) as given in Eqn. (7).

\[
\delta = \sin^{-1}\left(\frac{P \cdot X_L}{\sqrt{3} V_{inv} V_{grid}}\right)
\]
Because of the importance of the quality of the converter voltage for synchronization, SPWM is preferred as switching strategy, which is capable of generating a good quality sine wave output with low harmonic content at a modest carrier frequency of 4kHz, resulting in low switching losses [22]. This yields good efficiency and low component loss.

**D. Filter Design**

Fig. 8 shows the equivalent circuit of three-phase inverter connected to the grid. The switching frequency effects in the inverter can inject harmonics from the charging station to the grid. These harmonics requires the connection of low pass filter between the inverter and the grid. The filter attenuates most low order harmonics in the output.

The inductor (L) determines the ripple in the current and reduces the low frequency harmonic components. The voltage across the inductor (V_L) with respect to the switching frequency (f_{sw}) and ripple current (\Delta I_{inv}) is given by Eqn. (8).

\[ V_{dc} = L \Delta I_{inv} f_{sw} \]  

According to the harmonic standards, 15-20% of the rated ripple current is allowable; 20% is assumed in this work. The maximum ripple depends on the inductance, dc voltage (V_{dc}) and f_{sw}. The dc link voltage and switching frequency is constant and the inductance can be calculated from Eqn. (9).

\[ L = \frac{1}{8} \frac{V_{dc}}{\Delta I_{inv} f_{sw}} \]  

The high frequency components have to be eliminated from the inductor current when connected to the grid. This must be performed by the shunt impedance which is low at high frequencies. Assuming, I_{inv} is the inverter voltage, I_{inv} is the inverter current and Z_c, Z_t, Z_g and Z_{L1} are the impedances of the capacitor, transformer, grid network, and inductor respectively, then the ratio of inverter current and voltage is given in Eqn. (10).

\[ \frac{I_{inv}(s)}{V_{inv}(s)} = \frac{Z_c(s)}{Z_c(s) + Z_t(s) + Z_g(s) + Z_{L1}(s) + Z_{L2}(s) + Z_{L1}(s) + Z_{L2}(s) + Z_t(s) + Z_g(s)} \]  

Eqn. (10) given above is simplified as given in Eqn. (11) and therefore the value of capacitor (C) can be calculated from the formula derived as given in Eqn. (12) below.

\[ I_{inv} = \frac{1}{s^3 L_1 C (L_g + L_t) + s^2 L_t R_g C + s (L_1 + L_t + L_g) + R_g} \]

\[ C = \frac{V_{lim} - s (L + L_t + L_g) - R_g}{s^3 L_1 (L_g + L_t) + s^2 L_t R_g} \]  

**V. RESULTS AND DISCUSSION**

BCPT model explained in sections II, III and IV has been designed for a power handling capacity of 2kW and simulated for the circuit parameters shown in Table I. The battery specifications used are (200V, 5Ah and 30%), (250V, 7Ah and 40%) and (300V, 8Ah and 80%). Fig. 9 - Fig. 17 shows the simulation results of the proposed BCPT scheme and its performance during G2V and V2G mode operations.
To analyze the performance of the system under transient conditions, the simulations are shown here for 0.75s.

**TABLE III:** Circuit Parameters Of Proposed BCPT System

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>$C_{b1}, C_{b2}$</td>
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<td>5mH, 4.35mH</td>
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</table>

Fig.9 and Fig. 10, shows the detected angular frequency and load angle by the synchronization scheme for 2kW power transfer. The simulation result here gives 22°. Thus, these plots shows the effectiveness of the fuzzy based phase angle estimation scheme.

From Fig. 12, it can be noted that during V2G operation, the dc link voltage controller maintains the voltage input of the three-phase inverter to the peak voltage of the grid. This is important for synchronizing, the inverter voltage with the grid voltage.

Fig. 13 shows the rms waveform of power supplied to the grid. The initial sudden dip in the power value is due to synchronization action which occurs for a few milliseconds duration. The comparison between filtered and unfiltered voltage of the inverter during V2G mode of operation is shown in Fig. 14.

The square wave output waveform of inverter can inject harmonics in the grid voltage. Fig. 14 shows the filtered output waveform has a THD of 3.5% which is in acceptable level of IEEE 519 standard for harmonic limits.

Fig. 15 shows the load voltage curve in the secondary side is maintained constant to 200V. This is done, as the output voltage of the contactless system varies due to variable load.

Fig. 16 shows the transfer of 2kW power from grid to vehicle during G2V operation. Here, the positive convention of power denotes G2V operation and negative convention represents V2G operation. Fig. 17 shows the constant current charging of the battery for rating. The initial dip and in the output is caused due to synchronization action in the BCPT system. Initially, for synchronizing the BCPT system with the
utility grid, the primary side of BCPT system is maintained to a level of grid voltage. Due to this reason, their is dip in the current which is seen in Fig. 17.

It is observed from Fig. 9 - Fig. 17, the proposed charging system and its controllers works well for V2G and G2V operations.

VI. CONCLUSION

In this paper, a new concept of grid connected BCPT system with a fuzzy based phase angle estimation scheme has been presented. The proposed BCPT model represents both V2G and G2V operations. Fuzzy based phase angle estimation scheme is developed for synchronizing charging station inverter with the grid. DQ modeling of the proposed synchronization scheme is described and its features are explained. An investigation shows that the proposed method is fast, accurate, robust and simple. The complete BCPT system and its controllers are capable of supplying power through loose magnetic coupling in both directions. The result obtained from simulation shows the effectiveness of the proposed system, which successfully extracts symmetrical components and all useful signal information for transferring power on both sides.

REFERENCES