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REACTIVE POWER COMPENSATION USING VEHICLE-TO-GRID ENABLED BI-DIRECTIONAL OFF-BOARD EV BATTERY CHARGER

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Abstract:
This study examines the implementation of an external battery charger for the electrical vehicle that is connected to the grid and can also serve as a power generator (vehicle-to-grid) and a battery charger (grid-to-vehicle). The charger's topology includes a bidirectional converter composed of a grid-facing AC-DC cascaded H-bridge present on the front end and a DC-DC converter on the back end that controls power flowing between the battery of the vehicle and the power system. For safety measures, galvanic isolation is implemented on the user's side. The designed control algorithm regulates EV and battery currents using an active power instruction for grid-to-vehicle and vehicle-to-grid operation, in combination with reactive power instructions from the power system as necessary. The article offers an adaptive notch filter-based (ANF) control to calculate the system phase and sync the produced reference current, bypassing the requirement for a phase-locked loop (PLL) and by doing so minimizing controller design complexity while boosting steady-state and transient efficacy. The Simulink model of an external battery charger for the electric vehicle of 12.6 kVA was created in MATLAB software and the quality of the control algorithm is assessed during the operations of electric vehicle charger, such as vehicle-to-grid, grid-to-vehicle, and reactive power compensation mode.

Keywords: G2V, V2G, ANF, reactive power, Bi-directional electrical vehicle charger.

Introduction:

Autonomous vehicles (EVs) have become increasingly popular in developed economies due to their lower fuel use and emission of greenhouse gases. Exterior fast-charging stations with either bidirectional or unidirectional power electronic technologies have become more common. The two-way operation allows power flow to be supplied in both directions: from the grid to the vehicle and from the vehicle to the grid. The vehicle-to-grid operational mode is appealing in the grid because it can use the stored energy in the battery systems of an automation vehicle to fulfill the grid's storage requirements. However, battery degradation during V2G operation

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remains a concern. The proposed model in the paper focuses on designing an EV charger that provides reactive power compensation to the power grid. However, the use of batteries in the vehicle used, to regulate the DC link voltage to achieve uninterrupted reactive power compensation may reduce their performance and lifespan due to increased charging and discharging cycles. The chapter explains the EV charger's operation in the grid to vehicle and reactive power compensation modes, but not during the vehicle-to-grid mode. A multifunctional electric vehicle battery charger with both reactive power compensation capabilities is offered. The designed electric vehicle charger controller supports concurrent reactive power compensation in both operating modes, referred to as a vehicle for the grid mode. Galvanic isolation is included in the charger architecture for greater durability. The charger maintains a unified power factor during charging and employs an ANF for synchronization rather than a phase-locked loop for improved performance and lesser complications. The control loop employs direct power control for a quick dynamic reaction to power fluctuations, and the use of an adaptive notch filter rather than phase locked loop increases steady-state performance. The voltage of the DC link is maintained the same as the reference value by employing a DC link voltage term in the current control's inner loop.

Bi-Directional External Electric Vehicle Battery Charger:

An external electrical vehicle charger's architecture is in Figure 1. The electric vehicle charger shown serves to assess the charger's reactive power adjustment ability as well as its other two working modes. The H-bridge two-way converter on the front end of the power grid is a voltage source converter with only one stimulated voltage. Figure 2 depicts the circuit layout of the grid-facing converter in a detailed manner. Primary side of a single-phase toroidal core transformer is linked to each H-bridge output. Three of the transformers' secondary windings are in series connection with each other, the per-phase output voltage is obtained by the addition of secondary voltages of each transformer. Toroidal transformers' use at the output end improves their performance over traditional transformer-based prototypes. It also eliminates the need for voltage-comparing sensors, to maintain the same power distribution among the transformers that were initially required.

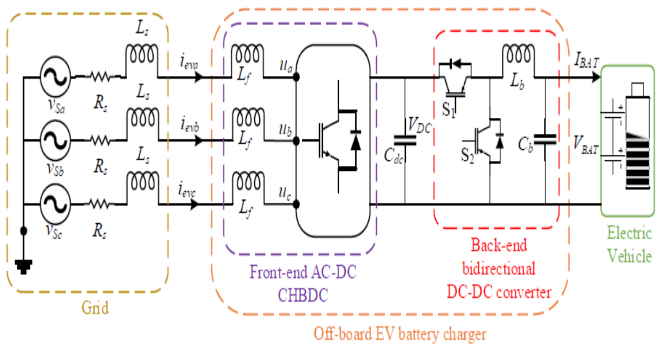

Figure 1, EV charger configuration.

As depicted in figure 1, the inductor(L) filter is made use to couple the grid and

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CHBDC facing power grid, this helps to improve the converter's output voltage quality. As it has multilevel construction, the switching harmonics of higher-level can be easily removed. The EV batteries are charged and discharged using the Buck-Boost DC-DC converter (BBDC) on the back end of the grid. Figure 1 depicts the BBDC's detailed circuit configuration. The given system can be operated in two modes by adjusting the two switches S1 and S2. The back-end converter acts as a buck converter by controlling switch S1 and boost operation is obtained by controlling S2. Thus, the alternate operation of buck and boost modes of BBDC can be used to charge and discharge the electric vehicle battery.

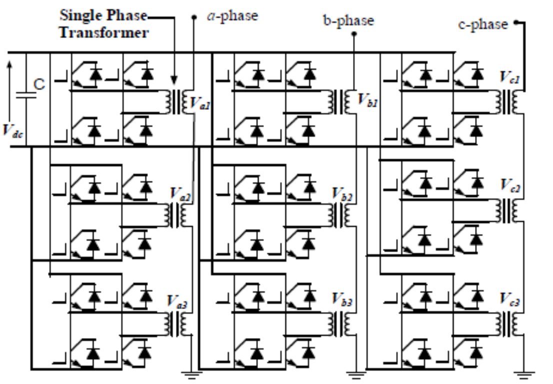

Figure 2, CHBDC circuit configuration

Working methodology of electric vehicle charger:

The device developed in this study has two primary goals: one, to charge the electric vehicle battery by drawing active power from the power grid (grid-to-vehicle), and two, to transfer active power back to the power grid when requested (vehicle-to-grid). Additionally, when the power system operator demands, it provides reactive power back to the grid. Figure 3 depicts the detailed controller structure. The designed control algorithm makes use of an adaptive notch filter.

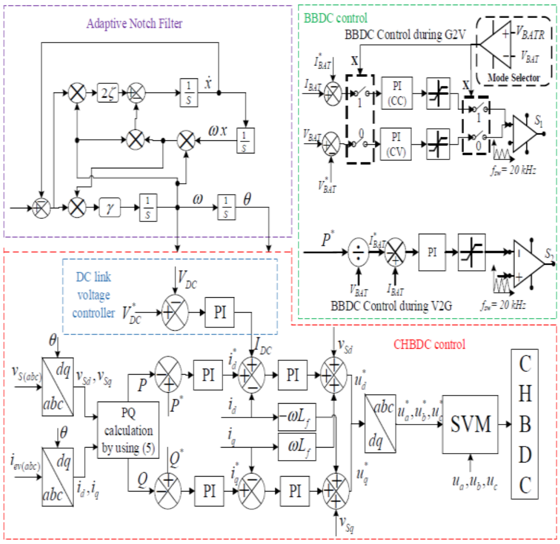

Figure 3

Adaptive notch filter operates successfully regardless of system disturbances and replaces the standard PLL. The equations of the adaptive notch filter are as follows:

$$\ddot{x} + \omega^2 x = 2\zeta\omega e(t)$$

$$\dot{\omega} = -\gamma x \omega e(t)$$

$$e(t) = u(t) - \dot{x}$$

(1)

The estimated frequency can be taken as ω and u(t) is considered as input taken, and ζ and γ are constants, whose values are real and positive. The adaptive notch filter's speed and accuracy can be decided by the selection of ζ and γ. U1 and ω1 are the amplitude and frequency of fundamental components.

$$\begin{pmatrix} x \\ \dot{x} \\ \omega \end{pmatrix} = \begin{pmatrix} -\frac{U_1}{\omega_1}\cos(\omega_1 t + \varphi_1) \\ U_1 \sin(\omega_1 t + \varphi_1) \\ \omega_1 \end{pmatrix} \quad (2)$$

The frequency and phase angle of grid voltage V_{sa} from a-phase is estimated from the adaptive notch filter structure as depicted in figure 3. The park transformation is used to move from the abc-framework to the dq-framework, as described below.

$$\begin{bmatrix} v_{Sd} \\ v_{Sq} \end{bmatrix} = [T] \begin{bmatrix} v_{Sa} \\ v_{Sb} \\ v_{Sc} \end{bmatrix}$$

here,

$$[T] = \sqrt{\frac{2}{3}} \begin{bmatrix} sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \end{bmatrix}$$

The above matrix [T] can be used for dq-transformation.

$$\begin{bmatrix} i_{Sd} \\ i_{Sq} \end{bmatrix} = [T] \begin{bmatrix} i_{Sa} \\ i_{Sb} \\ i_{Sc} \end{bmatrix} \quad (4)$$

By using the above equations, power P and Q can be calculated as shown below,

$$P = 3/2\left(v_{Sd} i_d + v_{Sq} i_q\right)$$
$$Q = 3/2\left(v_{Sq} i_d - v_{Sd} i_q\right) \quad (5)$$

The error signal, obtained after comparing the reference signals to the observed ones, is routed through controller and current i_d* , current I_q* are calculated. The P* is the active power instruction to charge or deliver battery power. The plus sign of P* reflects charging power drawn from the grid by the charger, while the opposite sign of P* represents active power from the battery. The Q* denotes the reactive power sought from charger by the grid. Positive Q* denotes the reactive power (inductive in nature) given to the grid from the battery charger. Negative Q* represents reactive power (capacitive in nature) given to the grid by the battery charger. The total active current component is obtained by addition of active current value and output current I_{dc}. The calculated power grid current is sent to the dq-frame, after comparing it to the reference currents. The output of the inner loop with PI control is first added to the matching calculated voltage of the grid in the dq-frame. The calculations are shown below:

$$u_d^* = u_d + v_{Sd} + \omega L_f i_q$$
$$u_q^* = u_q + v_{Sq} - \omega L_f i_d \quad (6)$$

The matrix [T] used for inverse transformation is given below.

$$[T]^{-1} = \sqrt{2/3} \begin{bmatrix} sin\theta & cos\theta \\ \sin(\theta - 2\pi/3) & \cos(\theta - 2\pi/3) \\ \sin(\theta - 2\pi/3) & \cos(\theta - 2\pi/3) \end{bmatrix} (7)$$

Aside from the charger's popular grid-to-vehicle and vehicle-to-grid working modes. The charger setup and controller are designed to operate in vehicle-for-grid mode on their own or in combination with grid-to-vehicle or vehicle-to-grid operational modes. This study discusses, also validates four charger working modes.

A. MODE-1 (grid-to-vehicle operation):

This mode is used to charge the batteries of electric vehicles and they are charged by drawing power from the power grid. During the charging of batteries, two methods are used, they are constant voltage and constant current methods. The minimum charging current is adjusted to the appropriate level with fixed current during the initial charging state until the voltage meets the maker's rated acceptable voltage rating. The battery is then charged at maximum voltage with reducing current till the current reaches its rated value and the voltage of the battery reaches maximum. During grid-to-vehicle operation the charging power instruction P* is followed by the CHBDC controller. The reactive power instruction Q* = 0 in this operating state. The switch S1 controls BBDC as a buck converter and is used to manage the I_{BAT}, and V_{BAT} of the electric battery. Figure 3 depicts the BBDC controller structure during G2V operation.

B. MODE-2 (vehicle-to-grid operation):

During the vehicle-to-grid operational mode, the vehicle charger sends energy to grid. When the electric vehicle is linked to the power grid, the charger's principal task is mode-1 functioning. However, power transmission across both directions is permitted for a short time with the inclusion of a BBDC. By setting the reference power instruction to a negative value and Q* = 0, the CHBDC is regulated in this mode of operation to ensure a 180-degree phase shift between EV current and grid voltage. The instruction to produce the reference signal is received by the charger control algorithm. Using equation 8, IBAT* can be determined while EV charger power losses are ignored.

$$I_{BAT}^{*} = \frac{P^{*}}{V_{BAT}}. \quad (8)$$

C. MODE-3(grid-to-vehicle with vehicle-for-grid):

During this operating mode, the electric vehicle charger provides reactive power assistance to the grid in addition to recharging the batteries. The charger controller supplies both inductive and reactive power to the power grid. The positive sign of power orders P and Q denoted battery charging with an inductive mode of assistance, while the negative sign of power command Q denoted capacitive reactive power. In Fig 3, the CHBDC controller receives the requisite power order and manages the CHBDC switching to satisfy the required power requirement.

D. MODE-4(vehicle-to-grid with vehicle-for-grid):

During this operating mode, the charger provides reactive power backup to the grid in addition to draining the stored energy in the batteries. The charger controller supplies inductive as well as capacitive reactive power to the grid. The power instruction P is always a negative real value in this mode. The positive sign of power command Q meant battery discharge with inductive reactive power support, while the negative sign denoted capacitive reactive power. In Fig 3, the CHBDC controller receives the relevant power instruction and handles the switching of the CHBDC to meet the required power requirement.

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Simulation Parameter Specifications:

Parameters	Specifications
Charger apparent power	12.6 kVA
CHBDC Filter	L_f=2.5 mH (25A)
BBDC elements	L_b=3.7mH, C_b=660μF
Grid Impedance (Z_s)	R_s=0.1Ω, L_s=1.6mH,
DC link Capacitor(C_{DC})	2200μF/500V
Transformer (CHBDC)	1kVA, 1-ϕ,Toroidal core
Supply System	230Vrms, 50Hz
EV Battery	Nominal voltage= 192V,

Table 1

Obtained Results:

To evaluate the suggested battery charger reliability during the charger's defined operating modes, a simulation model has been developed. The simulation parameters required in making the model are mentioned in the table. Vehicle charger begins operating in grid-to-vehicle mode, to charge vehicle battery with the understanding that reactive power will be supplied whenever it is needed from the power grid. If grid needs reactive power, the controller can function with different charging power. Figure 7 depicts the charger's performance corresponding to vehicle-to-grid mode. Figure 9 depicts the change from inductive to capacitive reactive power instruction. The results reveal that the charger current changes as expected.

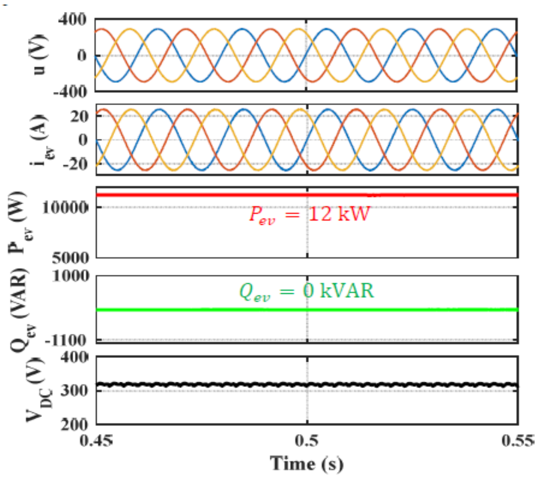

Figure 4, G2V operating mode

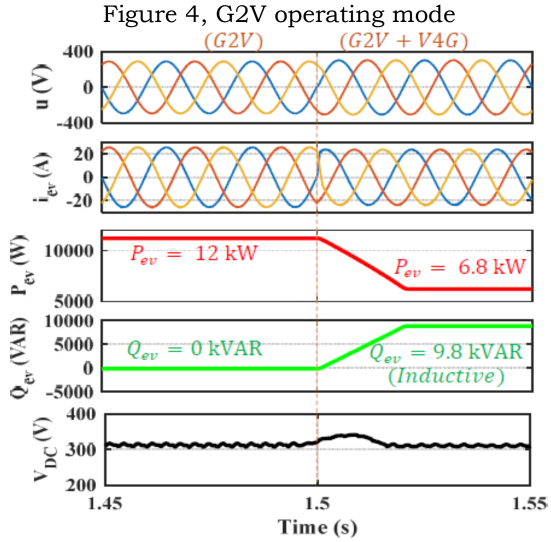

Figure 5

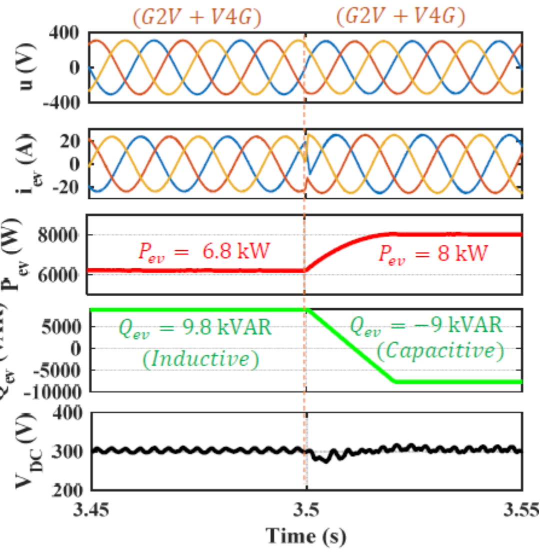

Figure 6

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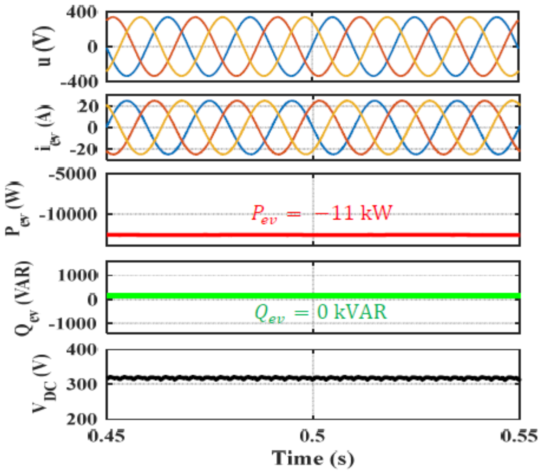

Figure 7, V2G operating mode

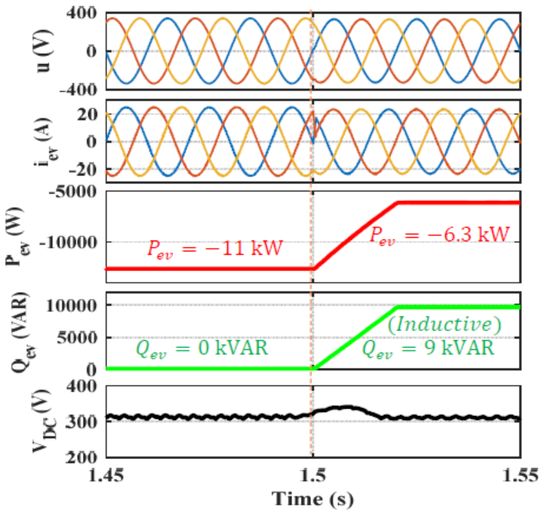

Figure 8

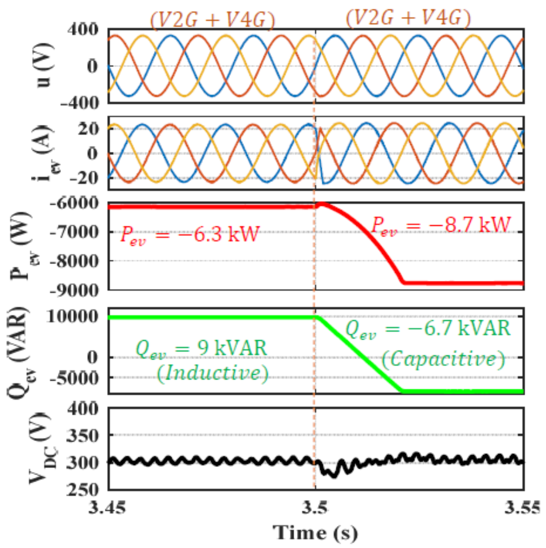

Figure 9

Conclusion:

This work proposes an efficient control technique that takes into account grid to vehicle and vehicle-to-grid i.e., modes 1 and 2, as well as reactive power adjustment, and incorporates electric vehicles as an integral part that may store, consume, and give energy. When the power instruction is delivered, the control algorithm created functions effectively in a variety of operating settings, and the modes of operation are well implemented. The charger performs admirably in both steady-state and dynamic modes. The off-board charger reacts to the instruction switch in less than two grid cycles. Reactive power operation does not affect the EV battery, hence extending battery lifespan. The results demonstrate the suggested controller performance under various power command circumstances successfully. The observed data indicate that the supplied charger is an excellent fit for the utility grid's reactive power support services.

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