IMPACT OF PENETRATION OF ELECTRIC VEHICLES ON INDIAN POWER GRID

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Abstract
The research on impacts of electric vehicles on Indian power grid is motivated to enhance development of electric vehicle in India against the burning issues of rising fuel demand and the nation’s dependency on other countries for fuel which largely affects the GDP of nation. India has declared E-mobility mission plan to deploy 4,00,000 passenger electric vehicles by 2020. If this target is achieved India can avoid importing 120 million barrels of oil and avoid 4 million tonnes of CO₂ emissions by 2020. In future, as demand of electric vehicles increases, charging issues while connecting electric vehicle to grid also increases. This paper presents various aspects in terms of challenges and issues when electric vehicle is charged from grid and also the benefits, potential services and applications of electric vehicle in V2G mode. Effect of electric vehicle penetration on distribution grid is carried out in matlab simulink environment to observe effects on different electrical parameters like dc bus voltage, current, active power, reactive power, harmonics and power factor. Concept of vector control technique for voltage source converter is developed for stabilizing grid against penetration of electric vehicle. Control technique implemented here gives fast dynamic response, reduces harmonics and improves power factor with constant dc bus voltage. Concept shown here will be very useful for fast dc charging of electric vehicle batteries. Battery modelling described with the concept of extracting parameters from manufacturers discharge characteristics gives fast and effective solution and will be useful for not only Li-Ion batteries but also for Ni-Mh and Lead-acid batteries.

Keywords: vectorcontrol,grossdomesticproduct,phaselocked loop,voltage source converter,mobility mission plan

1 INTRODUCTION
Globally the transportation systems are almost completely oil dependent and they are a significant source of green house gases and other emissions. Today’s energy policies lean strongly towards diversification of transportation fuels, improving energy efficiency and reducing emissions [1]. The use of grid connected vehicles offer great potential to fulfill these challenging
requirements. Electric vehicles are gaining worldwide interest and acceptance as a promising potential long term solution to sustainable personal mobility [1]. Transportation sector is responsible for 70% consumption of petroleum products in India [2]. Nation is largely dependent on other countries for rising demand of fuel which affects GDP (Gross Domestic Product) of the nation. Hence in near future it is expected that the adoption of electric vehicles will increase significantly. As penetration of electric vehicle increases there will be some serious challenges due to vehicle charging on power grid. The feasibility analysis of penetration of electric vehicles on grid is prime concern among the various issues. In 2007 PNNL (Pacific Northwest National Laboratory) has conducted research on impacts of PHEV deployment in US grid for light duty vehicles that could be supported by existing electrical infrastructure. The study covered 12 main regions of the U.S with an estimated 213 million LDVs (Light Duty Vehicles) converted to PHEVs with an all-electric range of 33 miles (PHEV33). For the electrical grid data, statistics were gathered for two 24-hour periods for summer day and winter day (for each of the 12 regions). Study revealed that with the existing infrastructure approximately 73% of the estimated PHEV could be charged. An assumption is made for 24-hour charging. For above 73% of PHEV out of 213 million LDVs (Light Duty Vehicles) annual U.S generation will increase by 910 billion kWh (+24%). Some other factors that affects the charging behavior of the EVs are type of connection i.e., unidirectional or bidirectional, number of vehicles charging in a given area, geographical location, levels of current and charging voltage, status of battery and its capacity, charging duration and slow or fast charging[3]. Fast charging has a great impact on grid distribution network because of high power i.e. typically more than double of an average household load [4]. Apart from the grid feasibility issues there are some other serious issues to be considered while charging of electric vehicles on power grid. These charging effects might result in power quality issues, increase in harmonics, increased transformer losses, increased line losses, line heating issues and increased reactive power consumption. Summarizing all these effects it might result in potential damage to the customer devices and power system equipments. These issues may cause overall power system and voltage stability problems and even collapses the system network [5], [6]. These issues can be reduced by charging of electric vehicles during off peak periods by coordinated or programmed charging of multiple EV’s in distribution grids [8] or by proper demand management of grid connected PHEV’s [10]. If coordinated charging is implemented for multiple PHEVs, grid enhancements or modifications will be significantly reduced. Proper energy management system along with the coordinated charging will help to perform demand response based EV charging. In other words, the EMS (Energy Management System) should be able to disconnect the EVs from the grid in case of overload [7]. Regarding control techniques researchers have done their work from proportional integral controllers and hysteresis controllers to fuzzy controllers. Researchers have used various fuzzy techniques for traffic management, forecasting of electrical load, control of dc-dc converters etc[11]. As nation is concerned regarding obstacles towards electric vehicle development, major concern in India at present is the feasibility of penetration of electric vehicle on Indian power grid. Comparing penetration of electric vehicles in US grid to the Indian grid then India is not even in a position at present to penetrate more than 10% of total vehicles if considered as electric vehicles. In many parts of India still generation is not matching the demand. Many distribution systems in India were designed decades ago considering the load levels and load characteristics of that time. Many of these power system networks do not have monitoring and automation capability and even enough spare capacity [7]. So sudden EV penetration in Indian power grid needs lot of thinking regarding redesigning power system networks [7]. Obstacles faced in development of electric vehicles in India can be eliminated by adopting following methods.

I. Increasing generation capacity and strengthen non renewable generation in country.

II. Region wise installed capacity of India as on 28th February 2014 is 237742.94 MW. Many generation and transmission projects are sanctioned and will be executed in near future. [12]

II. Co-ordinate charging

Coordinated charging means that vehicle charging is scheduled to occur at moments of low demand. Daily load curves should be studied carefully and from that off peak period should be identified for penetration of electric vehicles[12].

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III. Energy conservation principles
To enhance penetration of electric vehicles on Indian grid the country has to focus on energy conservation practices not only in Industries but also in villages where major chances of energy saving potential lies. Author was a part of Vishvakarma yojna in which energy losses were measured in 255 villages of Gujarat a state of India and solutions were suggested to mitigate them and corresponding reports were submitted to the authorities of Gujarat government [12].

In this paper vector control technique for fast dc charging of electric vehicle batteries is shown. Battery modelling described with the concept of extracting parameters from manufacturers discharge characteristics gives fast and effective solution and will be useful for not only Li-Ion batteries but also for Ni-Mh and Lead-acid batteries. Voltage source converter with battery algorithm based on extracting parameters from discharging characteristics stands true for reducing filter size while charging vehicles and gives fast and effective solution. Control technique with proper selection of dc bus capacitor reduces the size of filter. Vector control technique provides fast response to give constant dc bus voltage with unity power factor against the penetration of electric vehicle on fast charging mode. Alignment to a dq synchronous reference frame orientation with PI regulators is used in the control topology for decoupling purposes. In this voltage source converter synchronously rotating dq reference frame is used. Very important and necessary feature of grid side converter control is grid synchronization and for that PLL (Phase locked loop) is used. Vector control technique used here is based on inner and outer control loops. The inner loop controls power between dc link and grid while outer loop controls the dc voltage of the load. So the control technique implemented here gives fast dynamic response, reduces harmonics and improves the power factor with constant dc bus voltage. Concept shown here will be very useful for fast dc charging of electric vehicle batteries. Work carried out is explained in various sections. Section 2 consists of benefits, potential services and applications of V2G with quadrant operation of charger. Section 3 shows system configuration for proposed work done. Section 4 explains various power levels for battery charging and battery model. Section 5 explains basics of voltage source converter and section 6 explains vector control technique for voltage source converter. Section 7 is for results and discussion.

2 VEHICLE TO GRID
When electric vehicles are charging from grid then that mode of operation is known as grid to vehicles and when electric vehicles are delivering energy to grid than that mode of operation is known as vehicle to grid. In these section four quadrant operations along with benefits, potential services and applications of V2G is discussed.

2.1 Four Quadrant operation

![Figure 1 Modes of operation of charger](image)

The idea of V2G helps to build a whole set of instantly available distributed energy storage devices [11]. In V2G services vehicle operation is divided into four quadrants. When active and reactive powers both are positive then it is quadrant I operation and it refers to charging and inductive operation of charger. When real power is positive and reactive power is negative, it is quadrant IV operation charging and capacitive. When real power is negative and reactive power is positive it is quadrant II operation which is discharging and inductive and if real and reactive powers both is negative then it is quadrant III operation, discharging and capacitive. In this paper to study the effects of charging and to mitigate it, quadrant one operation is simulated.

2.2 V2G benefits, potential services and applications

The active power markets of V2G can be divided into four general groups [13]. These four groups are base load, peak, spinning reserves, and regulation. Bulk power generation that is running most of the time it is defined as base load. As V2G for base load applications requires large amount of power and large amount of batteries, it
is generally not preferable. Peak shaving occurs during predictable highest power demand hours. Ultra capacitors having high amount of power density is more suitable for meeting these peak demands in short time. Spinning reserves are supplied by generators having fast response time and ready to respond in case of equipment or power supply failures. Spinning reserves should be included in system power design to meet contract requirements and are typically called around 20 times a year[14]. The duration of supply by a spin reserve is typically around 10 min but the source must be able to last up to 1 hour. Active regulation is used to keep the frequency and voltage steady. Regulation is called for only a few minutes at a time, but the number of times can be up to 400–500 times per day. The utility pays spinning reserves and regulation sources in part for just being available, per hour availability; however, base load and peak shaving are paid per kWh generated[13].

### 3 System Configuration

![System Configuration Diagram](image)

Figure 2: System configuration for proposed work

Figure 2 shows the system configuration for analysing vehicle charging impacts. A 30 MVA generator is connected to 3-phase 3 level voltage source converter via transformer and grid filter. Function of filter is to reduce harmonics. In voltage source converter dc side ripples and harmonics in the system can be taken care by effective selection of dc capacitor. Specifications for proposed model are shown in table 1.

As shown in Figure 2 voltage source converters are connected to the ac system by means of transformers. The function of the transformer is to transform the ac voltage level to required ac voltage level for dc charging of vehicles. The phase reactors are used for controlling active and reactive power flow by regulating currents through them. Reactors also serve as filters and therefore reduce the high frequency harmonic contents of the ac currents which are caused by the switching operation of the IGBTs. The dc side contains two equally sized capacitors. The size of these capacitors depends on the required dc voltage. The primary objective of the dc capacitor is to provide low inductive path for the turn-off current and it also works as energy storage device to control the power flow. Capacitor also reduces the voltage ripple on dc side. Voltage source converters on the ac side act as a constant current source and therefore require an inductor as its energy storage. On the dc side voltage source converter acts as a constant voltage source and it requires capacitor as energy storage device. Loads are put on both ac and dc sides to study the battery charging impacts as it is in general practise. Model specification for the system configuration is shown in table 1.

| Description                  | Value                          |
|------------------------------|-------------------------------|
| Voltage source converter rating | 500 Volts DC, 500 kW         |
| AC Supply: three-phase system | 500 V, 30 MVA, 50 Hz          |
| Load                         | Ac side 1MW, dc side 400kw including electric vehicle |
| DcLink:2 capacitors          | 25000 mF                      |
| Switching Frequency          | 1620 Hz                       |

### 4 Charging Power Levels with Battery Model

Various power level chargers and infrastructure configurations are classified based on the amount of power required, charging time location and component ratings etc [9].

| Power Level types | Typical use                      | Expected power level | Charging time | Vehicle technology               |
|-------------------|---------------------------------|----------------------|---------------|---------------------------------|
| Level 1 US 120Vac | Charing at home or office       | 1.4 kW(12A)          | 4-11 hours    | PHEVs(5-15kWh)                  |
| EU230 Vac         |                                 | 1.9kW(20A)           | 11-36 hours   | EVs(16-50kWh)                   |
| Level 2 US 240Vac (EU) 400Vac (EU) | Charing at private or public outlet | 4kW(7A) 8kW(2A) 19.2kW(80A) | 1-4 hours 2-6 hours 2-3 hours | PHEVs(5-15kWh) EVs(16-30kWh) EVs(3-50kWh) |

Table 1: Model specifications

Table 2: Charging power levels [9]
Table 2 shows charging power levels. Typical use of level 1 charging is at home or office. Level 2 charging is used at private or public outlets. Level 3 is analogous to commercial filling station. Fast dc charging can be used for greater than 100kw power level and vehicle can be charged within 30 minutes. Level 1 and level 2 are onboard chargers and level 3 and dc chargers or charging stations are off board chargers.

Analysis is done to study effect of various electrical parameters while charging battery from the grid. To analyze the grid impact battery model used is free from algebraic loop problems.

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Figure 3 shows discharge characteristic of Li-Ion battery. Discharge characteristic can be simplified as shown in Figure 4 below.

Figure 3: Discharge characteristic of Li-Ion battery

Figure 4: Typical discharge curve

Shepherd model can represent accurately the voltage dynamics when the current varies and takes into account the open circuit voltage (OCV) as a function of SOC (State of charge). A term concerning the polarization voltage is added to better represent the open circuit voltage behavior and the term concerning the polarization resistance [22],[23]was slightly modified. The battery voltage obtained was given by

$$V_{batt} = E_0 - K Q_{Q-it} - Ri + Aexp(-B it) - R Q_{Q-it} i^* (1)$$

$$K Q_{Q-it} i^*$$ term refers to polarization voltage

Where

$$V_{batt} =$$ battery voltage V

$$E_0 =$$ battery constant voltage (V)

$$K =$$ polarization resistance ($\Omega$) or polarization constant(V/AH)

$$Q =$$ battery capacity (Ah)

$$i_t =$$ actual battery charge (Ah)

$$\Lambda =$$ exponential zone amplitude (V)

$$B =$$ exponential zone time constant inverse

$$R =$$ battery internal resistance ($\Omega$)

$$i =$$ battery current (A)

$$i^* =$$ filtered current

Particularity of this model was use of a filtered current i* flowing through the polarization resistance. This filtered current solves issue of algebraic loop problem due to the simulation of electrical systems in simulink. Finally, the OCV varies non-linearly with the SOC. This phenomenon was modeled by the polarization voltage term. Equation (1) is valid for the Li-Ion battery. For the other batteries (Lead-Acid, NiMH and NiCD), hysteresis phenomenon between the charge and the discharge should be taken into account irrespective of the SOC of the battery [22], [24]. It is very necessary to extract the parameters for the given battery while doing modeling in matlab, hence equation 1 should be simplified in steady state condition to reproduce manufacturers discharge curves. Generalized equation will be as under.

$$V = E_0 - K Q_{Q-it} i^* - R Q_{Q-it} i + C (2)$$

Comparing equation 1 with 2, the filtered current i* will be equal to i because current is in steady state.

Vehicle battery manufacturer provides datasheet which includes discharge characteristics. From the discharge characteristics it is possible to extract fully charged voltage ($V_{full}$), end of the exponential zone($Q_{exp}$), end of the nominal zone($Q_{nom}$), Maximum capacity($Q$) and the internal resistance R. With these 3 points calculation becomes much easier. The capacity $Q_{nom}$ is extracted from the battery until the voltage drops under the nominal voltage. Value should be between $Q_{exp}$ and $Q$ as shown in figure. The voltage $V_{exp}$ and the capacity $Q_{exp}$
corresponds to end of exponential zone. The voltage should be between \( V_{\text{nom}} \) and \( V_{\text{full}} \) and the capacity should be between 0 and \( Q_{\text{nom}} \) as shown in the figure.

For the fully charged voltage extracted charge is 0 (i\( t=0 \)) and the filtered current (i\( t \)) is 0 because current step has just begun.

\[ E_0 = V_{\text{full}} + K + R i - A \]  
For the end of the exponential zone the factor B can be approximated to \( \frac{3}{Q_{\text{exp}}} \) since the energy of the exponential term is almost 0 after 3 time constants.

\[ A = V_{\text{full}} - V_{\text{exp}} \]  
\[ B = \frac{3}{Q_{\text{exp}}} \]  

The filtered current (i\( t \)) is equal to i because the current is in steady state hence equation 1 can be modified as.

Li-Ion discharge model

\[ V = E_0 - K \frac{q}{q_{\text{it}}} i t - K \frac{q}{q_{\text{it}}} i - R i + C \]  

Where \( C = A e^{-\beta i t} \)  

Li-Ion Charge model

\[ V = E_0 - K \frac{q}{q_{\text{it}}} i t - K \frac{q}{q_{\text{it}}} i - R i + C \]  

Where \( C = A e^{-\beta t} \) same as 7.

Equation 6 and 8 suggests that the discharging characteristics used for parameter extraction stands true for evaluating charging impacts. From the manufactures discharge curve it becomes easy and effective to find E0.

Assumption made here is the internal resistance is constant during the charge and discharge cycles and does not vary with the amplitude of the current.

5 Voltaghe Source Converter

Thyristors can only be turned on (not off) by control action, and rely on the external ac system to affect the turn-off process. Control system only has one degree of freedom. With some other types of semiconductor device such as the insulated-gate bipolar transistor (IGBT), both turn-on and turn-off can be controlled, giving a second degree of freedom. As a result self commutated converters can be made by IGBTs that can be turned on and off many times per cycle in order to improve the harmonic performance. Voltage-source converters are compact as compared to line-commutated converters (mainly because much less harmonic filtering is needed). So VSC’s are preferred where space is prime consideration.

The VSC system incorporates advanced power electronics technology used in electric power systems and has the capability of transmitting large amount of active power over long distances. Fast and decoupled active and reactive power control can be achieved by voltage source converters [16]. The drawback of VSC’s is the bulky dimensions of dc-link capacitors, which is the main limiting factor. By reducing the dc-link capacitor size a reduction in cost and volume of the converter can be achieved. However, a small dc-link capacitance leads to large fluctuation in the dc-link voltage, and hence can cause semiconductor switch breakdown. The proposed work involves the control of converter dynamics. The idea is to control the exact amount of required current in the converter, to force the power balance. Hence, the dc-link voltage does not fluctuate even though a fairly small capacitance is utilized.

VSCs utilize self-commutating switches, e.g. gate turn-off thyristors (GTOs) or insulated gate bipolar transistors (IGBTs), which can be turned on or off in a controlled manner. VSCs operate at switching frequency utilizing Pulse-Width Modulation (PWM) technique. Advantages of implementing such a scheme is:

1. Active and reactive power can be controlled independently (to or from the Converter) without any needs for extra compensating equipment.
2. Little risk of commutation failures in the converter.
3. Faster dynamic response and reduced need for filtering and hence smaller filter size [15].
4. Minimal environmental impact.
5. Current smoothing is done by dc capacitor so small amount of filter size is required.

In an attempt to improve the poor harmonic performance of the two-level converter, some systems have been built with three level converters. Three-level converters can synthesize three (instead of only two) discrete voltage levels at the AC terminal of each phase: \( +\frac{1}{2} Ud \), 0 and \( -\frac{1}{2} Ud \). A common type of three-level converter is the diode-clamped (or neutral-point-clamped) converter, where each phase contains four IGBT valves, each rated at half of the dc line to line voltage, along with two clamping diode valves [16]. The dc capacitor is split into two series-connected branches, with the clamping diode valves connected between the capacitor midpoint and the one-quarter and three-quarter points on each phase. To obtain a positive output voltage (\( +\frac{1}{2} Ud \)) the top two IGBT valves are turned on,
to obtain a negative output voltage ($-\frac{1}{2} Ud$) the bottom two IGBT valves are turned on and to obtain zero output voltage the middle two IGBT valves are turned on. In the latter state, the two clamping diode valves complete the current path through the phase.

Figure 5 shows three phase three level voltage source converter. It is also called as neutral clamped converter. In a refinement of the diode-clamped converter, the so-called active neutral-point clamped converter, the clamping diode valves are replaced by IGBT valves, giving additional controllability. Normally, converters are connected to the ac system by means of transformers. The most important function of transformers is to transform the ac voltage level to the dc voltage level. Usually, they are single-phase three-winding type, but depending on the transportation requirements and the rated power, they can be arranged in other ways [18]. The phase reactors are used for controlling active and reactive power flow by regulating currents through them. The reactors also serve as ac filters and therefore reduce the high frequency harmonic contents of the ac currents which are caused by the switching operation of the IGBTs. The dc side contains two equally-sized capacitors. Size of these capacitors depends on the required dc voltage. The primary objective of the dc capacitor is to provide a low inductive path for the turned-off current [18] and also works as energy storage device to be able to control the power flow. The capacitor also reduces the voltage ripple on the dc side. Ac filters prevent the voltage harmonics entering the ac system. VSC on the ac side acts as a constant current source and therefore requires an inductor as its energy storage device. A small ac filter for harmonics elimination is also required on the ac side. On the dc side VSC acts as a constant voltage source and it requires a capacitor as its energy storage device. Energy storage capacitor here provides dc filtering capability.

The control system of VSC has a fast inner current control loop that controls the ac currents. The ac current references are provided by the outer controllers [19]. The slower outer controllers can be the dc voltage controller, the ac voltage controller, the active power controller, the reactive power controller and the frequency controller. Thus, the reference of the active current can be obtained from the dc voltage controller, from the active power controller or from the frequency controller [17].

6 CONTROL ALGORITHM FOR PROPOSED SCHEME

Vector current control is the most popular control method used for VSC. Dc-link voltage regulation is achieved by implementing a control based on the energy stored in the dc-link capacitor. Alignment to a dq synchronous reference frame orientation with PI regulators is used in the control topology for decoupling purposes. In voltage source converter synchronously rotating dq reference frame is used and active and reactive power can be independently controlled. Very important and necessary feature of grid side converter control is grid synchronization and for that PLL (Phase locked loop) is used. Vector control technique used here is based on inner and outer control loops. The inner loop controls power between dc link and grid while outer loop controls the dc voltage of the load. So the control technique implemented here gives fast dynamic response, reduces harmonics and improves the power factor with constant dc bus voltage. Concept shown here will be very useful for fast dc charging of electric vehicle batteries. Voltage source converter with proposed control technique can be utilized in all four quadrants for effective V2G operation. Vector control scheme is shown in Figure 6.

Figure 6: Vector current principle

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By utilizing synchronously rotating dq reference frame, independent active and reactive power control is possible. Initially, system currents and voltages are described as vectors in a stationary αβ reference frame and then they are transformed to the rotating dq coordinate system. The transformation to dq coordinates is done as follows. Three-phase components $x_a(t)$, $x_b(t)$ and $x_c(t)$ are first described as two vectors in the αβ reference frame.

Using a park transformation, the transformation from αβ frame to dq can be written as

$$X_{dq} = X_{αβ}e^{-jθ}$$  \hspace{1cm} (9)

The vectors $x_a(t)$ and $x_b(t)$ are rotating with the angular frequency $ω(t)$, which is the angular frequency of the grid voltage in rad/s. Let $θ(t)$ be the angle defined by integrating $ω(t)$. Then the expanded matrix form of park transformation is obtained as

$$\begin{bmatrix} x_d(t) \\ x_q(t) \end{bmatrix} = \begin{bmatrix} \cos(ω(t)) & \sin(ω(t)) \\ -\sin(ω(t)) & \cos(ω(t)) \end{bmatrix} \begin{bmatrix} x_a(t) \\ x_e(t) \end{bmatrix}$$  \hspace{1cm} (10)

Vectors $x_d(t)$ and $x_q(t)$ represent currents, where $x_d(t)$ is the current which gives required power to the dc bus and $x_q(t)$ is the current which defines the reactive power condition. Excellent controlling is achieved with this transformation and it is shown in vector control block of figure 6 as $I_{dq}$. A correct transformation requires an exact value of the angle $θ(t)$ to decouple the components for independent power control. The angle $θ$ is given as:

$$θ = \tan^{-1}\left(\frac{V_b}{V_a}\right)$$  \hspace{1cm} (11)

Where $V_a$ and $V_b$ are voltage components in the αβ reference frame. Synchronization technique phase locked loop is utilized to compute value of the angle $θ$ [20]. The phase-locked loop is used to synchronize the turning on/off of the power devices, calculate and control the flow of active/reactive power by transforming the feedback variables to a reference frame suitable for control purposes [20]. Vector control system is primarily based on inner and outer control loops, inner loop controls power between dc link and grid while outer loop controls the dc voltage of the load.

### 6.1 Phase locked Loop

The phase locked loop measures the system frequency and provides the phase synchronous angle $θ$ (more precisely $[\sinθ, \cosθ]$ for dq transformation block[21]). Very important and necessary feature of grid side converter control is the grid synchronization. The synchronization algorithm is able to detect the phase angle of grid voltage in order to synchronize the delivered power. The purpose of this method is to synchronize the converter output current with the grid voltage in order to obtain a unity power factor. The inputs of the PLL model are the three phase voltages measured on the grid side and the output is the tracked phase angle. The PLL model is implemented in synchronous dq reference frame, where a park transformation is used. The phase-locking of the system is realized by adjusting the q-axis voltage to zero. A PI controller is used for this purpose. The grid angle is obtained by integration of the angular frequency. The grid angle is introduced in the park transform to calculate the dq voltage components.

### 6.2 Control strategy

The control strategy of voltage source converter as discussed has its base level and a fast inner current control loop that controls ac currents. The ac current references are provided by the outer controllers. The outer controller is dc voltage controller. Thus the reference of active current can be obtained from the dc voltage controller. The inner loop controls power between dc link and grid while outer loop controls the dc voltage of the load.

#### 6.2.1 Inner current loop

![Figure 8: structure of inner current loop](Image)
The inner controller or current controller as input takes the error between the reference current and measured current. Error is carried through the PI regulator and the decoupling terms are compensated by feed-forward. As a result the desired converter voltage in dq reference frame is obtained. The feed-forward is used to minimize disadvantage of slow dynamic response of cascade control. As the reference values of the inner loop variables are often available, these are fed forward for a faster and safer operation.

The structure of the block of current controller (inner current loop) of figure 6 is shown in Figure 8. The controller in Figure 8 consists of two PI regulators, for q and d axis respectively. Active current (id) is used to control active power flow or dc voltage level. Similarly, reactive current (iq) is used to control reactive power flow into grid.

### 6.2.2 Outer controller

![Outer controller diagram](image)

The outer controller (outer current loop) is given by:

\[
V_{dref} = V_{dc} - \left( K_p + K_i/\omega_L \right) I_d^* - \left( K_p + K_d/\omega_L \right) \dot{I}_d
\]

Figure 9: Outer controller

Figure 9 represents the dc voltage controller, outer control loop of Figure 6. Output of Id* of output dc voltage regulator block (outer loop) is given to current controller (Inner current loop).

### 6.2.3 Overall control scheme

![Overall control scheme diagram](image)

The controller within the AC/DC converter manipulates the q axis current to achieve unity power factor operation, while the d axis current is being used to regulate dc link voltage as shown in Figure 10. It is assumed that the dq frame is rotating at \( \omega \) speed and the d axis is oriented along the grid voltage vector. The value of \( i_q \) ref is set to zero to get unity power factor.

### 7 System description & results

Uncontrolled rectifier is simulated in Matlab simulink environment under different load condition and reduction in dc bus voltage with ample current harmonics was observed. Uncontrolled rectifier was replaced by 12 pulse voltage source converter and disturbance in electrical parameters was stabilized against increase in load. On this stable grid Li-ion batteries were connected and again the variation in electrical parameters was stabilized by using vector control technique for multi pulse converter. Initially the proposed matlab model is simulated on uncontrolled rectifier. As the load is increased from 200kW to 400kW the dc bus voltage immediately drops to 270V. Similar loading was done on controlled rectifier. It can be observed that the dynamic response of the dc regulator to this sudden load variation is acceptable. The dc voltage is back to 500V within 1.5 cycles and the unity power factor on the ac side is maintained. So it is verified that the system is stable.

On this stable grid batteries with Li-ion chemistry were connected and the impact on various electrical parameters on grid was observed with battery charged from fully discharge condition. While battery charging constant dc bus voltage was achieved at unity power factor at source side with vector control logic. Results obtained from simulation are summarized below.

| Description                              | Value                  |
|------------------------------------------|------------------------|
| Uncontrolled Rectifier                   |                        |
| Controlled rectifier with Li-Ion Battery | 250 volt, 6.5 Ah      |
| Controlled rectifier with Li-Ion Battery | 250 volt, 30 Ah       |

| DC bus voltage | Active power | Reactive power |
|----------------|--------------|----------------|
| V_{dc}=270 V  | 138×10^6 W  | 6.5×10^6 W    |
| V_{dc}=500 V  | Active power=1.36×10^6 W | Active power=1.43×10^6 W |
| V_{dc}=500 V  | Active power=1.43×10^6 W | Active power=1.626×10^6 W |
| V_{dc}=500 V  | Active power=1.36×10^6 W | Active power=1.43×10^6 W |
| V_{dc}=500 V  | Active power=1.36×10^6 W | Active power=1.43×10^6 W |

Table 3: Results obtained from simulation
Figure 11 shows dc bus voltage of uncontrolled rectifier. As load increases the dc bus voltage drops considerably in uncontrolled rectifier. Ideally it should remain at 500 volt. So before connecting EV batteries to grid this drop in voltage should be stabilized.

| Voltage harmonics | Voltage harmonic | Voltage harmonics | Voltage harmonics |
|-------------------|------------------|-------------------|-------------------|
| 1.48%             | 0.19%            | 0.21%             | 0.23%             |

| Current harmonics | Current harmonic | Current harmonics | Current harmonics |
|-------------------|------------------|-------------------|-------------------|
| 43.17%            | 8.33%            | 7.28%             | 4.91%             |

| Power factor     | Power factor     | Power factor     |
|------------------|------------------|------------------|
| 0.997            | 0.997            | 0.9999           |

Figure 12 shows considerable amount of current harmonics in the supply system due to uncontrolled rectifier.

For implementing control strategy, as discussed and as shown in the figure 13 Iqref is set to zero for unity power factor. Variation of modulation index, Id and Iq are also shown in the figure 13.

Figure 13 Variations in Id, Iq and modulation index.

Figure 14 shows that constant dc bus voltage is achieved with controlled rectifier. Control strategy is already discussed for achieving constant voltage at dc bus side and unity power factor at source side.

Figure 15 shows that as supply voltage harmonics are negligible a sinusoidal supply is obtained with the active converter.

Figure 16 shows that in case of controlled converter supply current harmonics are reduced as compared to the uncontrolled case.
Figure 16: Supply current harmonics of controlled rectifier

Figure 17 shows that even with battery impact the terminal voltage can be obtain constant with proper selection of dc bus capacitor and control logic discussed earlier. Once the dc bus voltage is stabilized distribution grid is ready to take the electric vehicle load.

Figure 17: Constant dc bus voltage with controlled rectifier and battery

Figure 18 shows the supply voltage and current are in phase irrespective of the loading which gives excellent power factor.

Figure 18 source voltage and current

Figure 19 shows that with proper selection of filter, dc bus capacitor and vector control technique harmonics are obtained within the standards.

Figure 19: Supply current harmonics of 30AH battery connected to grid

8 CONCLUSION

The proposed model used for analysing grid impacts can be used for dynamic conditions. It has certain advantages as compared to basic battery models. Simulation is done in three parts. First the load is increased at the bus with uncontrolled rectifier and voltage reduction at dc bus and increase in current harmonics are observed. Then this bus is stabilized by control rectifier (Active converter) and constant dc bus voltage at unity power factor at the source side is achieved. On this stable grid Li-ion batteries are charged and impact of vehicle on grid is analysed and again the dc bus voltage is regulated, harmonics are controlled with unity power factor at source side. With vector control logic, variation in electrical parameters can be mitigated when batteries are charged from the grid even from fully discharged condition. Concept shown here will be very useful for fast dc charging of electric vehicle batteries. Battery modelling shown with the concept of extracting parameters from manufacturers discharge characteristics gives fast and effective solution and will be useful for not only Li-Ion batteries but also for Ni-Mh and Lead-acid batteries.
9 REFERENCES

[1] Ahmed M.A Haider, Kashem M. Muttaqi, Danny Sutanto “Technical challenges for electric power industries due to grid-integrated electric vehicles in low voltage distributions”. A review by published in Energy conversion and management Elsevier 86 (2014) 689–700.

[2] All India study on sectoral demand of diesel and Petrol-2013 by Petroleum Planning and Analysis Cell of Ministry of Petroleum and Natural Gas, Government of India.

[3] Kintner-Meyer MCW, KP Schneider, and RG Pratt, 2007, “Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional US Power Grids Part I: Technical Analysis.” Online Journal of EUEC 1: paper # 04.

[4] Putrus G. A, Suwanapingkarl P, Johnston D, Bentley E. C, Narayana M. "Impact of Electric vehicles on power distribution network". Published in IEEE transctions.

[5] C.H. Dharmakeerthi, N. Mithulananthan, T.K. Saha. "Impact of electric vehicle fast charging on power system voltage stability", published in Electrical power and energy systems Elsevier, 57(2014)241-249.

[6] Omer C. Onar, Student Member IEEE, and Alireza Khaligh, Senior Member IEEE, "Grid Interactions and stability analysis of distribution power network with high penetration of plug in hybrid Electric vehicles." Published in IEEE transactions.

[7] Das T, Aliprantis DC. “Small-signal stability analysis of power system integrated with PHEVs”, published at ENERGY 2008, IEEE:2008,p.1-4.

[8] El Chehaly M, Saadeh O, Martinez C, JoosG, "Advantages and applications of vehicle to grid mode of operation in plug-in hybrid electric vehicles". In Electrical power & energy conference (EPEC), 2009 IEEE; 2009. p. 1–6.

[9] OnarOC, Khaligh A."Grid interactions and stability analysis of distribution power network with high penetration of plug-in hybrid electric vehicles". In: Twenty-fifth annual IEEE applied power electronics conference and exposition (APEC); 2010. p. 1755–62.

[10] Murat Yilmaz, Philip krein." Review of charging power levels and Infrastructure for Plug-in Electric and Hybrid Vehicles". Published in IEEE transctions.

[11] Salman Habib, Muhammad Kamran, Umar Rashid "Impact analysis of vehicle to grid technology and charging strategies of electric vehicles on distribution networks". A review published at journal of power sources 277(2015)205-214.

[12] Kashyap Mokariya, Varsha shah, Makarand Lokhande "Feasibility and penetration of electric vehicles in Indian power grid"; published at waset, International journal of electrical, computer and communication engineering vol 9.no,2,2015.

[13] Javiersolono Martinez, Jerome mulot, Fabien harel "Experimental validation of type two fuzzy controller for energy management in hybrid electric vehicle", published in Engineering application of Artificial intelligence, 26(2013).

[14] Kempton W, Tomic, J. “Vehicle-to-grid power implementation from stabilizing the grid to supporting large-scale renewable energy”. J. Power Sources 2005, 144, 280–294.

[15] Peterson, S.B. “Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization”. J. Power Sources 2010, 195, 2385–2392.

[16] A E. Michael Bahrman, Rich Haley, "Asynchronous Back-to-Back HVDC link with voltage source converters,” presented at the Minnesota power systems conference, 1999.

[17] V. G. Agelidis, et al., “Recent advances in high-voltage direct-current power transmission systems,” in Industrial technology, 2006. ICIT 2006. IEEE International Conference on, 2006, pp. 206-213.

[18] Xiangwu Yan, Member, IEEE, Bo Zhang, Xiangning Xiao, Member, IEEE, Huichao Zhao, Liming Yang, “A Bidirectional Power Converter for Electric Vehicles in V2G Systems”.

[19] C. Du, “The control of VSC-HVDC and its use for large industrial power systems,” PhD, department of electric power engineering, chalmers university of technology, Goteborg, 2003.

[20] D. S. Cuiqing, A. Bollen, M. H. J., “Analysis of the control algorithms of voltage-source converter HVDC,” in power tech, 2005 IEEE Russia, 2005, pp. 1-7.

[21] S. K. Chung, “Phase-locked loop for grid-connected three-phase power conversion systems,” Electric power applications, IEEE proceedings -, vol. 147, pp. 213-219, 2000.

[22] Shepherd, C. M., design of primary and secondarycells - Part 2. An equation describing battery discharge, Journal of electrochemical society, Volume 112, July 1965, pp 657-664.

[23] Olivier Tremblay, Louis-A. Dessaint, “Experimental validation of a battery dynamic model for EV applications”, EVS24 Stavanger, Norway, May 13 - 16, 2009.

[24] Rynkiewicz, R., “Discharge and charge modeling of lead acid batteries”, applied power electronics conference and exposition, 1999. APEC ‘99. Fourteenth annual, vol.2, pp.707-710 vol.2, 14-18 Mar 1999.

[25] Feng Xuyun, Sun Zechang, “A battery model including hysteresis for State-of-charge estimation in Ni-MH battery”, Vehicle power and propulsion conference, 2008.VPPC ’08. IEEE, vol., no., pp.1-5, 3-5 Sept. 2008.