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Constant Switching Frequency Hierarchical Deadbeat Predictive Direct Power Controller with Dynamic Power Estimator for 3L-ANPC AFE Rectifier for EV Charger Applications

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# Abstract:

In this paper, a novel constant switching frequency hierarchical deadbeat predictive direct power controller with dynamic power estimator (HDP-DPC-DPE) is proposed for the 3-level active-neutral-point-clamped (3L-ANPC) active-frontend (AFE) rectifier for electric vehicle (EV) charger applications. In the proposed HDP-DPC-DPE, two new deadbeat predictive controllers are proposed for the outer dc-link voltage and the inner power control loops. First, a novel deadbeat predictive controller using DPE is proposed for the outer-loop dc-link voltage control of the AFE rectifier. Second, a novel constant switching frequency deadbeat DPC is suggested for the inner-loop power control. The proposed HDP-DPC-DPE is robust to power grid distortion due to elimination of the phase locked loop (PLL). Moreover, the proposed HDP-DPC-DPE provides fast dynamic response, robustness to parameters variations, constant switching frequency, continuous sinusoidal input current and unity PF. The performance and feasibility of the proposed HDP-DPC-DPE for the 3L-ANPC AFE rectifier are verified by the simulation results.

# SECTION I. Introduction

Increasing trend toward employing the EVs in the transportation fleet necessitates higher demand of the EV fast and ultra-fast charging stations. The EV fast and ultra-fast chargers power can be increased over 1MW for all-electric battery-powered Class 8 semi-trailer truck. As a part of ARPA-E CIRCUITS program, a project proposal entitled high power density 1MHz, 1MW, three-phase AC to DC ultra-fast EV charger has been suggested to develop high power density, lightweight, high efficiency, and high switching frequency EV mega-charger. Hence, integration of high power EV mega-chargers to the power grid imposes major challenges on both EV and power grid. The main challenges are voltage regulation during EV charger load variations, robustness to power grid distortion and parameters variations, continuous sinusoidal input current as well as unity PF.

Because of high-power and medium voltage operation capability, reduced EMI, improved THD, lower *dv*/*dt*, reduced switching frequency and losses, improved power grid side quality as well as higher efficiency, multilevel converters (MLC) can be considered as among the most promising solutions for various industrial applications such as AFE rectifier for EV mega-chargers [1[2][3][4][5][6]–7]. A MW-scale EV charger based on the 3-level neutral-point-clamped (NPC) converter has been presented in [8]. By applying the 3L-NPC converter, the AFE rectifier input filter size is notably decreased which results in higher power density AFE rectifier. However, uneven power loss distribution between power devices is main drawback of 3L-NPC AFE rectifier.

Moreover, to achieve high precision output dc voltage, continuous sinusoidal input current with low THD, unity PF as well as fast transient response, employed control technique plays crucial and undeniable role in AFE rectifiers. Various control methods have been proposed to improve dynamic performance of AFE rectifier. In [9], a cascaded dual model predictive control (MPC) method has been proposed for AFE rectifier. The energy function is employed in outer dc-link voltage controller and corresponding reference current is used for AFE rectifier inner control loop. Even though the proposed controller is robust to parameters variations, it has variable switching frequency, provides the AFE rectifier reference current instead of reference power, and it suffers from energy function incremental values problem. In [10], a finite-control-set MPC (FCS-MPC) with dynamic references has been proposed for AFE rectifier. Even though the proposed FCS-MPS with dynamic references provides fast dynamic response, it has variable switching frequency and it depends on the converter parameters such as load resistance. Hence, it is not robust to parameters variations and mismatches. In [11], a dc-link voltage predictive controller has been proposed for AFE rectifier. The proposed controller employs the output power and the energy stored in the dc-link capacitor to achieve fast dynamic response. However, it has variable switching frequency and it depends on the load value. Moreover, due to employing an integrator to calculate power variations, it suffers from integrator windup problem. Furthermore, the current loop and power controllers are two major applied control techniques to inner control loop of AFE rectifiers. The power control methods in AFE rectifiers are classified to indirect and direct power control (DPC) techniques. The internal current loop and modulator are not required in conventional DPC and the converter switching states are selected from switching table [12[13][14]–15]. However, the main drawbacks of conventional DPC are variable switching frequency and requiring to high sampling frequency. Therefore, to overcome mentioned drawbacks, the predictive controller has been applied to DPC by using PWM method. Hence, the constant switching frequency of AFE rectifier is obtained by employing PWM method [16[17][18]–19]. In [16, 18], the measured input currents and voltages as well as the reference and measured active and reactive powers are employed in the predictive control algorithm in *d-q* rotary reference frame to provide the rectifier average reference voltage vector. Hence, the predictive control algorithm requires PLL to convert the measured parameters, also to calculate the reference voltage vector in *d-q* rotary reference frame. Therefore, the performance of the predictive DPC highly depends on PLL accuracy and deteriorates in distorted power grid.

In this paper, to overcome above-mentioned drawbacks, the HDP-DPC-DPE method with constant switching frequency is proposed for the 3L-ANPC based AFE rectifier for EV charger. The proposed HDP-DPC-DPE comprises two novel deadbeat predictive controllers for the outer dc-link voltage and the inner power control loops. First, a novel deadbeat predictive controller using DPE is designed for the outer-loop dc-link voltage control of the AFE rectifier. The proposed dclink voltage deadbeat predictive controller based on the DPE is robust to parameters variations and mismatches and has fast dynamic response. This progress is obtained by integrating the parameters variations and mismatches into the DPE. Second, a novel constant switching frequency deadbeat DPC is suggested to the inner-loop power control. The PLL is eliminated from the proposed deadbeat DPC by employing stationary reference frame instead of *d-q* rotary reference frame. Hence, it leads to robustness of the proposed DPC to power grid distortion. The rectifier average voltage vector is calculated in stationary reference frame in each PWM period by the proposed DPC to real-time control of active and reactive powers. Then, the provided average voltage vector in stationary reference frame is converted to *abc* reference frame to generate related switching signals. The 3L-ANPC AFE rectifier uses the phase disposition PWM (PDPWM) method to generate switching signals. Hence, the proposed HDP-DPC-DPE provides fast dynamic response, robustness to parameters and power grid distortion, constant switching frequency, continuous sinusoidal input current and unity PF.

# SECTION II. The 3L-Anpc Based Afe Rectifier Controlled By the Proposed Hdp-Dpc-Dpe

## A. State Space Model of Controller using DPE for the AFE Rectifter Based on the 3L-ANPC Converter

Fig. 1 presents the proposed 3L-ANPC based AFE rectifier using the proposed HDP-DPC-DPE. As shown in Fig. 1, the three phase supply voltages , , connected to the 3LANPC converter using the input inductors with internal resistance . The discrete-time state space model of the proposed AFE are expressed as

(1)

where

(2)

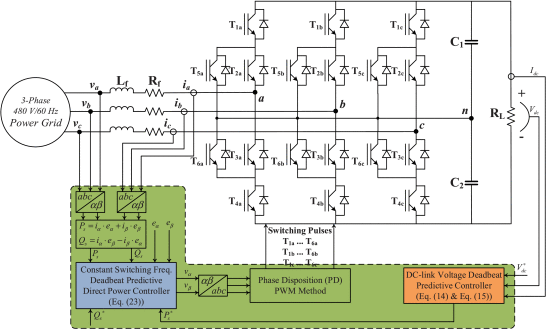
(3)

where V\_{dc} and I\_{dc} are the AFE rectifier output dc voltage and load dc current, respectively. is the AFE rectifier output dc capacitor, and T\_{s} is sampling time. Moreover, S\_{a}, S\_{b}, and S\_{c} are the switching states of the 3L-ANPC converter each leg and are illustrated in Table 1.

**TABLE 1** Switching States of Each Leg of the 3L-Anpc Converter.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |
| +1 | 1 | 1 | 0 | 0 | 0 | 1 |  |
| 0(U2) | 0 | 1 | 0 | 0 | 1 | 0 | 0 |
| 0(U1) | 0 | 1 | 0 | 1 | 1 | 0 | 0 |
| 0(L1) | 1 | 0 | 1 | 0 | 0 | 1 | 0 |
| 0(L2) | 0 | 0 | 1 | 0 | 0 | 1 | 0 |
| -1 | 0 | 0 | 1 | 1 | 1 | 0 |  |

where . In Table I, the switch is ON when it is 1 and is OFF when it is 0.



**Fig. 1.** The proposed 3L-ANPC based AFE rectifier using the proposed HDP-DPC-DPE.

Regarding (1) to (3) and Table I, the AFE rectifier has nonlinear time variable state space model. Hence, the cascaded controllers including the outer dc-link voltage and the inner power control loops are used to control the AFE rectifier. Generally, the PI controller is applied to the outer-loop dclink voltage control and MPC methods are limited to use for the inner-loop current or power control loops. However, the linear controller is difficult to design and presents a restricted dynamic behavior for dc-link voltage control. In this paper, the HDP-DPC-DPE, which consists of two new deadbeat predictive controllers for both the outer-loop dc-link voltage and the inner-loop power control, is proposed. The new robust and fast dc-link voltage deadbeat predictive controller using DPE is suggested to the outer-loop dc-link voltage control of the AFE rectifier. Moreover, the novel constant switching frequency deadbeat DPC is provided for inner power control loop of the proposed HDP-DPC-DPE. As shown in Fig. 1, the proposed inner-loop deadbeat predictive DPC with constant switching frequency is applied to the 3LANPC AFE rectifier for power control whereas the suggested outer-loop dc-link voltage deadbeat predictive controller is used to provide corresponding reference value from reference dc-link voltage.

## B. The Proposed Outer-loop DC link Predictive Controller using DPE for the AFE Rectifier

In the proposed DPE for the AFE rectifier, the dc-link voltage is regulated by adjusting the input power reference. The dynamic power equation of the AFE rectifier is expressed as

(4)

In (4), the AFE rectifier input ac side power is defined as the left-hand side of the equation and the AFE rectifier output dc side power is expressed as the right-hand side of the equation. Moreover, the active  and reactive  power of the AFE rectifier input ac source are defined as

(5)

(6)

By substituting (5) and (6) in (4), the AFE rectifier ac side input power is defined as

(7)

where  is the output dc side power of the AFE rectifier and  is the input voltage amplitude. In addition, the predicted value of the AFE rectifier dc side output power is expressed as

(8)

where P\_{r}(k+1) is the predicted value of the AFE rectifier dc side output power, P\_{r} is the load active power, and  is the required active power of the dc-link capacitor during transient conditions to reach  reference dc-link voltage. Based on the deadbeat predictive method strategy, the dc side output power of the AFE rectifier reference value  at  and its predicted value  at  should be equal. Thus,

(9)

 is the load active power and is given by

(10)

 is the required active power of the dc-link capacitor during transient conditions to reach  reference dc-link voltage and is calculated as

(11)

where P\_{c}(k) is the power of the dc-link capacitor at and E\_{c} is the stored energy in dc-link capacitor. By employing the Euler forward approximation,  can be expressed as

(12)

Hence,  is calculated as

(13)

Accordingly, by substituting (10) and (13) in (9),  is expressed as

(14)

Considering (7), the reference value of the AFE rectifier ac side input power  is defined as

(15)

Accordingly, (14) and (15) are the proposed deadbeat predictive DPE for the outer-loop dc link voltage control. Therefore, by employing (14) and (15), the reference value of the AFE rectifier ac side input power (P\_{s}^{\*}(k+1)) is calculated based on the reference value of dc-link voltage (V\_{dc}^{\*}(k+1)). The P\_{s}^{\*}(k+1) power reference has good dynamic performance by estimating the output dc side power P\_{r}^{\*}(k+1) by (14). Moreover, the parameters variations and mismatches are integrated to  which leads to robustness of the proposed deadbeat predictive DPE to parameters variations and mismatches.

## C. The Proposed Inner loop Constant Switching Frequency Deadbeat Predictive DPC for the 3L-ANPC AFE Rectifter

Similar to presented approach in [19], the proposed deadbeat predictive DPC is implemented in  stationary reference frame to eliminate the PLL. The measured input voltages and currents as well as the calculated  and  are converted to  stationary reference frame. In the proposed deadbeat predictive DPC,  and  reference voltage vectors are calculated based on the  and  reference values as well as the measured , , , and  values in each sampling period . Then, the corresponding , , and  reference voltages are applied to the 3L-ANPC converter controlled by the PDPWM method to provide the switching signals with constant switching frequency.

The input current dynamic equation of the AFE rectifier is defined as

(16)

By applying Euler forward approximation,  is expressed as

(17)

Hence, assuming , the inductor current between two sampling instants is calculated as

(18)

With regard to the fact that the sampling frequency  is much higher than the fundamental frequency of the power grid, the power grid voltage is considered as constant between two sampling instants, then . Hence, active and reactive power variations between two sampling instants in  stationary reference frame is determined as

(19)

By substituting (18) in (19),

(20)

In order to satisfy the deadbeat predictive DPC control rule, the  and  reference values should be equal to the  and  predicted values. Hence, (20) can be represented as follows

(21)

In the AFE rectifier, the  to achieve PF=1 and the  is determined by the outer-loop dc link voltage deadbeat predictive controller based on the proposed DPE in (14) and (15). Therefore, the  is estimated by applying the following linear approximation

(22)

By substituting (22) in (21), the proposed deadbeat predictive DPC control rule of the 3L-ANPC AFE rectifier is obtained as follows

(23)

In (23),  and  are the active and reactive power tracking errors, respectively.

# SECTION III. Simulation Results

The 3L-ANPC AFE rectifier controlled by the proposed HDP-DPC-DPE and the conventional deadbeat DPC controllers has been simulated in MATLAB/Simulink platform to verify the performance and feasibility of the proposed HDP-DPC-DPE controller. The main parameters of the simulated 3L-ANPC AFE rectifier are presented in Table II.

**TABLE 2**Main Parameters of the Simulated 3L-Anpc Afe Rectifier.

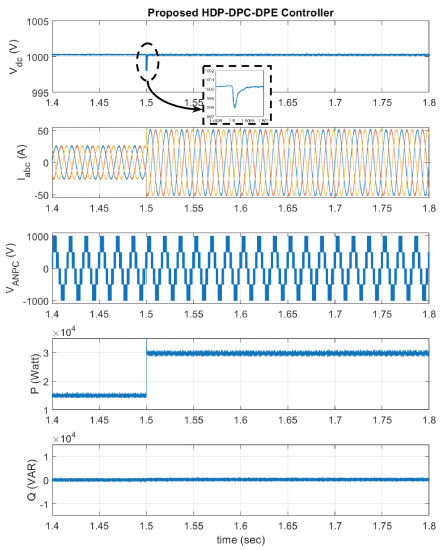
|  |  |
| --- | --- |
| Parameters | Value |
| AC grid line voltage |  |
| AC grid frequency |  |
| AFE nominal power |  |
| AFE input inductor |  |
| resistance of AFE input inductor |  |
| 3L-ANPC output capacitors |  |
| Outer loop DPE sampling time |  |
| Inner loop DPC sampling time |  |
| 3L-ANPC switching frequency |  |
| AFE rectifier output voltage |  |

Simulation results of the 3L-ANPC AFE rectifier controlled by the proposed HDP-DPC-DPE and the conventional deadbeat DPC controllers are presented in Figs. 2 and 3, respectively. As depicted in Fig. 2, by applying the proposed HDP-DPC-DPE controller, the transient time of dclink voltage regulation during load step change from 15 kW to 30 kW is only 500μ*s* and the undershoot is only 2*V*, whereas as shown in Fig. 3, by employing the conventional deadbeat DPC, the transient time of dc-link voltage regulation is 200*ms* and the undershoot is 85*V*.

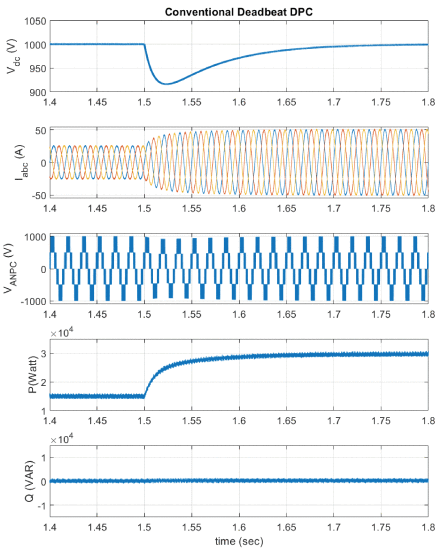
Moreover, Fig. 4 presents the output dc-link voltage, the input line current, the 3L-ANPC line voltage, and the active power of the 3L-ANPC AFE rectifier controlled by the proposed HDP-DPC-DPE controller during low voltage ride through (LVRT). As a worst-case scenario of LVRT, the input grid supply is disconnected at 1.8*s* and connected back at 2*s*. As illustrated in Fig. 4, the proposed HDP-DPC-DPE controls the 3L-ANPC AFE rectifier after LVRT and tracks the reference dc voltage and active power.

# SECTION IV. Conclusion

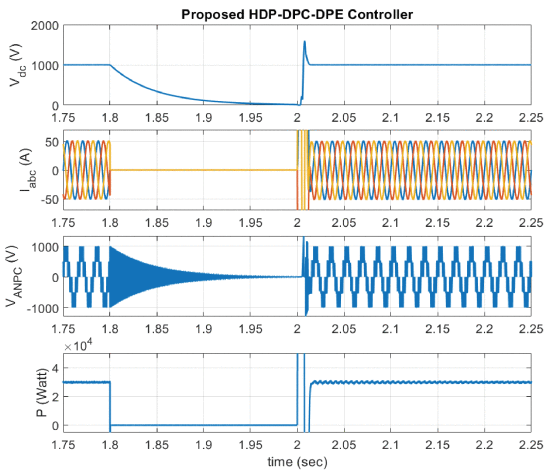
The constant switching frequency HDP-DPC-DPE controller was proposed for the 3L-ANPC AFE rectifier for EV charger applications. It consists of two proposed deadbeat predictive controllers for the outer dc-link voltage and the inner power control loops. The deadbeat predictive controller using DPE and the constant switching frequency deadbeat DPC controller were proposed for the outer-loop dc-link voltage control and the inner-loop power control of the AFE rectifier, respectively. Detailed theoretical analyses of two proposed deadbeat controllers as well as simulation results were presented and compared. The proposed HDP-DPC-DPE has provided fast dynamic response, robustness to parameters variations, constant switching frequency, continuous sinusoidal input current and unity PF.

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**Fig. 2.** The dc link voltage , input current , ANPC line voltage , active power , and reactive power of the 3L-ANPC AFE rectifier using the proposed HDP-DPC-DPE controller.

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**Fig. 3.** The dc link voltage , input current  ANPC line voltage , active power , and reactive power of the 3L-ANPC AFE rectifier using the conventional deadbeat DPC controller.

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**Fig. 4.** The dc link voltage , input current , ANPC line voltage , and active power of the 3L-ANPC AFE rectifier controlled by the proposed HDP-DPC-DPE controller during LVRT.

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