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High-Frequency-Link Vienna Rectifier with Power Quality Added Function

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Abstract:

The aim of this paper is to introduce power quality added function to the standard Vienna rectifier in order to compensate reactive power and to cancel current-type harmonics drawn by nonlinear loads connected to the same point of common coupling. A theoretical investigation that demonstrates the ability of such topology to compensate harmonics and limited reactive power is first presented. Then, the design and implementation of a linear quadratic regulator with integral action is presented. The converter is controlled as a whole i.e., a multiple-input-multiple-output system, and uses an augmented model that was developed in the d- q frame. Experimental results obtained with a digital-signal-processor-based DS1103 controller and the converter operating at a 20-kHz switching frequency proved the effectiveness of the theoretical study and the high performance of the proposed control strategy in compensating load harmonics and limited reactive power.

Introduction

NOWADAYS, active rectifiers are widely used in industrial applications in order to meet the international power quality standards. These rectifiers ensure that the input currents have a near-sinusoidal shape and are in phase with the mains voltage .Currently, a large variety of such rectifiers is available; however, the three-phase/switch/level boost rectifier known as the Vienna rectifier has already proven its effectiveness as a high-power rectifier. The topology has fewer active switches, a smaller filter inductor size, and better efficiency compared with the traditional six-switch two-level converter. The same advantage regarding energy efficiency of the Vienna rectifier used as a machine-side converter instead of a traditional six-switch two-level pulse width modulation (PWM) rectifier is also reported in the literature for wind energy conversion systems. Recently, efforts have been made by researchers to improve the Vienna rectifier's modeling and control and to increase its power density.

Power quality issues are now directly addressed in power conversion processes at both the generation and distribution levels. The trend is then to integrate power quality functionality into the converters control algorithms. The Vienna rectifier with active filter added function in three-phase three-wire and three-phase four-wire systems is reported in the literature, respectively, in However, in those studies, there is no indication on the amount of harmonics that can be compensated by the Vienna rectifier. On the other

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hand, the linear quadratic regulator (LQR) based on optimal control was successfully applied to three-phase PWM rectifiers and inverters, interfacing renewable energy sources to the utility grid using a three-level inverter and a three-phase three-wire shunt active power filter.

CONVERTER MODEL

The topology of the three-phase/switch/level boost rectifier known as the Vienna rectifier and the nonlinear load represented by a three-phase diode bridge $R-L$ loaded are shown in Fig. 1. A state-space model in the d–q rotating reference frame at the mains angular frequency ω of the Vienna rectifier is presented in [29]. The zero-sequence components of mains voltages and currents are equal to zero for a balanced three-phase source voltage and a nonconnected neutral point. The four state variable equations describing the system dynamics in the d–q rotating frame are given in the

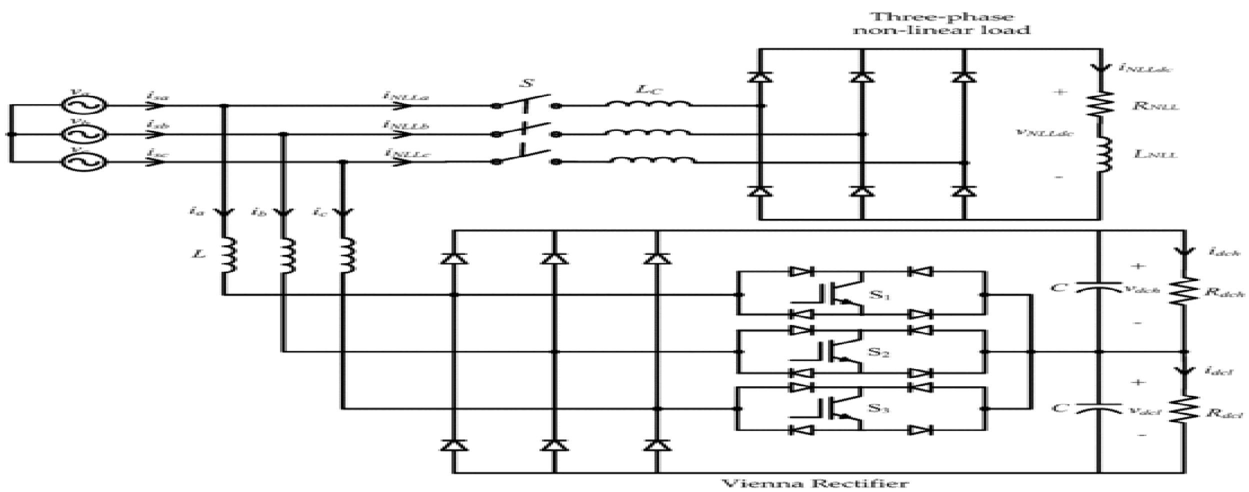

Fig. 1. System under study.

following:

$$v_d = L\frac{di_d}{dt} - L\omega i_q + \frac{v_{dc}}{2}d'_d \quad (1a)$$

$$v_q = L\frac{di_q}{dt} + L\omega i_d + \frac{v_{dc}}{2}d'_q \quad (1b)$$

$$C\frac{d(\Delta v_{dc})}{dt} = \alpha d'_o\left(i_d\cos\varphi_1 + i_q\sin\varphi_1\right) - \frac{3}{2}\frac{\Delta v_{dc}}{v_{dc}}\left(d'_d i_d + d'_q i_q\right) - i_{dh} + i_{dcl} \quad (1c)$$

$$C\frac{dv_{dc}}{dt} = \frac{3}{2}\left(d'_d i_d + d'_q i_q\right) - \alpha\frac{\Delta v_{dc}}{v_{dc}}d'_o\left(i_d\cos\varphi_1 + i_q\sin\varphi_1\right) - i_{dh} - i_{dcl} \quad (1d)$$

$$\left[v_d \quad v_q \quad v_o\right]^T = \mathbf{K}\left[v_a \quad v_b \quad v_c\right]^T \quad (1e)$$

$$\left[i_d \quad i_q \quad i_o\right]^T = \mathbf{K}\left[i_a \quad i_b \quad i_c\right]^T \quad (1f)$$

$$\left[d'_d \quad d'_q \quad d'_o\right]^T = \mathbf{K}\left[d'_a \quad d'_b \quad d'_c\right]^T \quad (1g)$$

$$d_k = 1 - d'_k\,\mathrm{sgn}(i_k). \quad (1h)$$

The subscripts a, b, and c are for the variables in the a–b–c frame, and the subscripts d, q, and o are for the variables in the new d–q rotating frame. Variable v is for voltages, variable i is for currents, and variable d is for duty cycles. The subscript k is equal to a, b, or c, respectively, for phase a, b, or c; and $\mathbf{K}$ is the Park's transformation matrix given by

$$K = \frac{2}{3}\begin{bmatrix} \sin\omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t - \frac{4\pi}{3}\right) \\ \cos\omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t - \frac{4\pi}{3}\right) \\ \frac{3}{2} & \frac{3}{2} & \frac{3}{2} \end{bmatrix}. \quad (1i)$$

expressions (1a)–(1h), $[i_d \; i_q \; \Delta v_{dc} \; v_{dc}]^T$ and $[d'_d \; d'_q \; d'_o]^T$ represent the state-space vector and the control input vector, respectively. The overall dc output voltage is $v_{dc} = v_{dch} + v_{dcl}$, the dc output voltage unbalance is $\Delta v_{dc} = v_{dch} - v_{dcl}$ and represents the difference between the upper and lower dc bus voltages, φ_1 denotes the phase shift between the phase voltage and the corresponding Vienna rectifier fundamental component current, sgn represents the function signum, and α is a constant parameter theoretically equal to $(2/\pi)$.

The state-space model (1a)–(1d), which is valid for large-signal operation, is nonlinear since it contains multiplication terms of the state variables and inputs. This nonlinear model has to be linearized around a set point in order to implement a linear controller such as the LQR.

The equilibrium point is obtained by making the time derivatives of (1a)–(1d) equal to zero and by substituting all variables by their steady-state values. The nominal steady-state operating point when the d-axis is aligned with the phase a voltage is

$$v_d = V\sqrt{2},\; v_q = 0,\; i_d = I_d,\; i_q = I_q,\; v_{dc} = V_{dc}$$

then

$$R_{dch} = R_{dcl} = R_{dc},\; i_{dch} = i_{dcl} = \frac{V_{dc}}{2R_{dc}},\; \Delta v_{dc} = 0. \quad (2)$$

The small-signal model (3) is obtained using linearization around the aforementioned operating point. The LQR control law essentially gives a multivariable proportional regulator. Integral action has been added to the controller in order to cancel steady-state errors. Three new states are then added to the small-signal model. These new state variables are the integral of the state variables $i_{q\sim}$, $\Delta v_{dc\sim}$, and $v_{dc\sim}$.

Thus

$$\frac{d\mathrm{x}_{a\sim}}{dt} = \mathrm{A}_a \cdot \mathrm{x}_{a\sim} + \mathrm{B}_a \cdot \mathrm{u}_\sim + \mathrm{E}_a \cdot \mathrm{v}_\sim \quad (3a)$$

$$\mathrm{x}_{a\sim} = \Big[i_{d\sim} \quad i_{q\sim} \quad \Delta v_{dc\sim} \quad v_{dc\sim} \quad \int i_{q\sim} \int \Delta v_{dc\sim} \quad \int v_{dc\sim} \Big]^T \quad (3b)$$

$$\mathrm{u}_\sim = [d'_{d\sim} \quad d'_{q\sim} \quad d'_{o\sim}]^T \quad (3c)$$

$$\mathrm{v}_\sim = [v_{d\sim} \quad v_{q\sim}]^T. \quad (3d)$$

In (3b)–(3d), vectors $\mathbf{x}_{a\sim}$, $\mathbf{u}_\sim$, and $\mathbf{v}_\sim$ are the augmented state, control, and disturbance vectors, respectively.

The matrices $\mathbf{A}_a$, $\mathbf{B}_a$, and $\mathbf{E}_a$, which represent the state, control, and disturbance matrices of the augmented system, respectively, are computed and presented.

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$$\mathbf{A}_a = \begin{bmatrix} 0 & \omega & 0 & -\frac{D'_d}{2L} & 0 & 0 & 0 \\ -\omega & 0 & 0 & -\frac{D'_q}{2L} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{2CR_{\mathrm{dc}}} & 0 & 0 & 0 & 0 \\ \frac{3D'_d}{2C} & \frac{3D'_q}{2C} & 0 & -\frac{1}{CR_{\mathrm{dc}}} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{B}_a = \begin{bmatrix} -\frac{V_{\mathrm{dc}}}{2L} & 0 & 0 \\ 0 & -\frac{V_{\mathrm{dc}}}{2L} & 0 \\ 0 & 0 & \frac{a}{C}(I_d \cos\varphi_1 + I_q \sin\varphi_1) \\ \frac{3I_d}{2C} & \frac{3I_q}{2C} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

as
$$\mathbf{E}_a = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (3e)$$

wherethe duty cycles in steady-state are given

$$D'_d = \frac{2(V_d + L\omega I_q)}{V_{\mathrm{dc}}} \quad (3f)$$

$$D'_q = -\frac{2L\omega I_d}{V_{\mathrm{dc}}} \quad (3g)$$

by $D'_o = 0.$ (3h)

Equation (1d), which represents the power balance between the ac and dc sides of the converter, gives for a lossless one

$$I_d = \frac{V_{\mathrm{dc}}^2}{3V_d R_{\mathrm{dc}}}. \quad (3i)$$

For the converter including power quality added function, in order to compensate for reactive power, the q-component of the Vienna rectifier I_q is computed as follows:

$$I_q = -I_{\mathrm{NLL}q} = -\sqrt{2} I_{\mathrm{NLL1}} \sin\varphi_1. \quad (3j)$$

In the preceding equation, $I_{\mathrm{NLL}q}$ represents the q-component of the fundamental currents drawn by the nonlinear load,

SIMULATION RESULTS & DISCUSSIONS

The system's response, as obtained on the matlab-based control algorithm, is presented here. The weighting matrix $\mathbf{Q}$ and weight W have been set to values that guarantee satisfactory response. It is a heuristic method, and it is important to point out that increasing the weight for a variable leads to a speedup of its response and vice versa. Weights Q and W are chosen to get duty cycles between zero and one and a settling time between one and two cycles of the supply mains. These values are first generated by simulation-based examination of the responses obtained using MATLAB's Sim Power Systems and Simulink,

$$Q_{i_d} = 5.10^6 \text{ c.u.}/\text{A}^2, \qquad Q_{i_q} = 5.10^7 \text{ c.u.}/\text{A}^2$$

$$Q_{\Delta v_{\mathrm{dc}}} = Q_{v_{\mathrm{dc}}} = 5.10^3 \text{ c.u.}/\text{V}^2, \quad Q_{\int i_q} = 5.10^3 \text{ c.u.}/\text{A}^2$$

i.e., $Q_{\int \Delta v_{\mathrm{dc}}} = Q_{\int v_{\mathrm{dc}}} = 1 \text{ c.u.}/\text{V}^2, \qquad W = 10^6 \text{ c.u.}$

A. Standard Vienna Rectifier

Fig.2 shows the phase voltage v_a, line current i_{sa}, upper dc bus voltage v_{dch}, and the opposite of the lower dc bus voltage $-v_{\mathrm{dcl}}$ when switch S is open (the three-phase nonlinear load is not connected) and the value of the resistors at the dc side of the Vienna rectifier is $R_{\mathrm{dch}} = R_{\mathrm{dcl}} = 40\ \Omega$

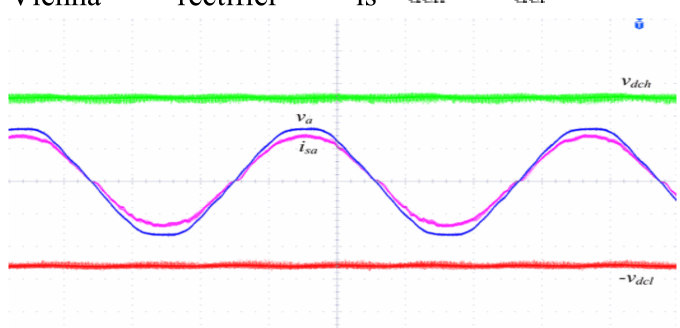

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Fig. 2. Phase voltage (ch1), upper dc bus voltage (ch2), opposite of the lower dc bus voltage (ch13), and source current (ch4) waveforms of the standard Vienna rectifier.

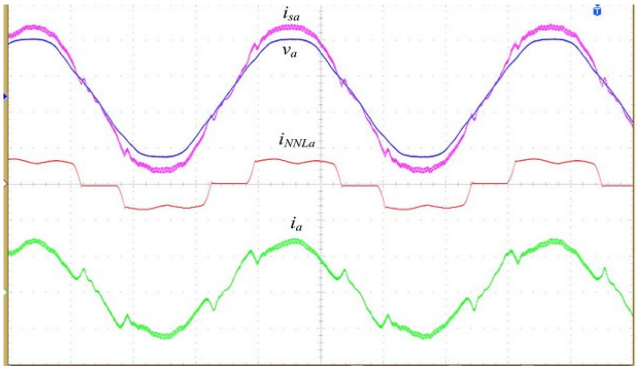

Fig. 3. Source voltage (ch1), source current (ch3), nonlinear load current (ch2), andVienna rectifier with power quality added function current (ch4)waveforms

The measured characteristics of phase voltages and line currents are summarized in Table I.

TABLE I PHASE VOLTAGES
AND LINE CURRENTS CHARACTERISTICS

The measured characteristics of power are summarized in Table II.

TABLE I
PHASE VOLTAGES AND LINE CURRENTS CHARACTERISTICS

	RMS	THD-F(%)
Phase voltage	120.6(V)	2.2
Source current	10.1 (A)	2.2

TABLE II
POWER CHARACTERISTICS

P(W)	Q(VAR)	S(VA)	DPF	PF
3600	0	3600	1	1

TABLE II POWER CHARACTERISTICS

The controller ensures the equalization of voltages across the two capacitors and tracking of the overall dc bus voltage, which is equal to its reference value. In addition, one can observe that the harmonic content and the displacement factor are kept under control. The source current's measured total harmonic distortion (THD) is equal to 2.2% for a fundamental component of 10.07 A, and that of the source voltage is also equal to 2.2%. This demonstrates the unity power factor operation of the standard Vienna rectifier.

B. Vienna Rectifier With Power Quality Added Function

1) Steady-State Regime

Fig. 3 shows from top to bottom the phase voltage , source current , nonlinear load current , and Vienna rectifier current when switch S is closed (the three-phase nonlinear load is now connected with , and the value of the resistors at the dc side of the Vienna rectifier is. The measured characteristics of nonlinear load and line

TABLE III NONLINEAR LOAD
AND LINE CURRENTS CHARACTERISTICS

The measured characteristics of nonlinear load and source power when the Vienna rectifier is supplying 1.8 kW to the dc load are summarized in Table IV.

TABLE IV NONLINEAR LOAD
AND SOURCE POWER CHARACTERISTICS

One can observe that the controller ensures the equalization of voltages across the two capacitors and tracking of the overall dc bus voltage, which is equal to its reference value. In addition, one can observe that

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the harmonic content and the displacement factor are kept under control.

The THD value of the measured line currents is 3.9% for a fundamental component of 7.54 A. The measured THD value of the nonlinear load currents is 24.5% for a fundamental component of 2.48 A. It can be observed from these results the ability of the Vienna rectifier with power quality added function to provide the required compensation for harmonics and reactive power.

TABLE III
NONLINEAR LOAD AND LINE CURRENTS CHARACTERISTICS

	RMS(A)	THD-F(%)
Nonlinear load current	2.56	24.5
Source current	7.58	3.9

TABLE IV
NONLINEAR LOAD AND SOURCE POWER CHARACTERISTICS

	P(W)	Q(VAR)	S(VA)	DPF	PF
Nonlinear load	870	90	930	0.99	0.95
Source	2730	0	2730	1	1

DYNAMIC REGIME

Fig. 4 (a) and (b) shows, when switch S is also closed, from top to bottom the overall dc bus voltage , phase voltage , source current , and the nonlinear load current when a sudden variation of the three-phase nonlinear load occurs. The power transmitted to the load has been increased from 50% to 100% and back to its initial value (is switched from 160 to 80 and back to 160). Compensation is achieved before and after load changes. The controller ensures tracking of the dc bus voltage, and the steady-state error is zero. A small overshoot–undershoot (4%) and a short settling time of the dc bus voltage (one cycle of the mains) for these load power variations can be noticed. In addition, one can observe that the harmonic content, as well as the compensation, is kept under control.

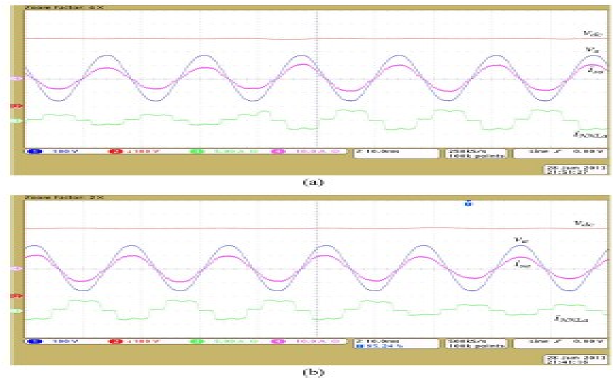

Fig.4. Overall dc bus voltage (ch2), phase voltage (ch1) source current (ch3), and nonlinear load current (ch4) of the Vienna rectifier with power quality added function current waveforms for nonlinear load variation. (a) From 50% to 100%. (b) From 100% to 50%.

CONCLUSION

In this paper, power quality added function of the Vienna rectifier has been first theoretically investigated. The ability of such a unidirectional power flow converter to compensate current harmonics and a small amount of reactive power was demonstrated. The boundaries for active and reactive power of the nonlinear load that can be connected at the PCC as a function of the Vienna rectifier active power with full compensation for harmonics and reactive power are then established. The active power of the nonlinear load can be as high as 1.2288 times that of the Vienna rectifier if the latter is only compensating the harmonics. As for the reactive power compensation, only a maximum of 10.6% of active power is reachable, which is obtained when the active power of the Vienna rectifier is half that of the nonlinear load. This ability is sufficient to compensate for reactive power drawn by diode bridge rectifiers, even when a large commutation inductor is used. The active power of the nonlinear load is equal to that of the Vienna rectifier for a commutation reactance as high as 0.1628 p.u. in the nonlinear load basis. An LQRI based on an extended small-signal state-space averaged model of the Vienna rectifier in the rotating – reference frame, including an integral action to complement the standard LQR and incorporating power quality added function, is then designed and implemented. The experiments that were carried out to compensate the current harmonics and the reactive power drawn by a diode bridge type of nonlinear load have proven the validity of the theoretical study and the effectiveness of the adopted control strategy

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