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Spoiler effects reduction with using active power filter on a direct torque controlled induction machine

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Abstract

Harmonics, which may be placed in electrical systems, have important effects on performance parameters of electrical motors. In this paper, effects of electrical power system voltage harmonics on torque position of induction motors are dealt with. System modeling with Pulse Width Modulation (PWM) type Active Power Filter (APF) is used for reducing these effects. APF, as a subsystem, is placed into torque control system entrance to save the control system and induction motor output torque. Motor outputs, that are before-after APF connections, are handed for understanding effects of voltage harmonics. Since APF design was based on voltage harmonics, Electromagnetic Interference (EMI) has not changed. Main goal of the filter is zero effect of voltage harmonics on motor torque. A new place is selected for APF and the filter control system is designed with using Lyapunov function at the same time. Classical PI controlled APF is used like as a reference filter system and final result is that motor and system elements are defended by nonlinear controlled APF.

Key Words: *Nonlinear control, Lyapunov theory, active power filter, direct torque control*

1. Introduction

Power quality is an index to the quality of current with voltage, that are placed on system frequency, for industrial, commercial and household consumers of electricity. Voltage waveform quality at the entry point of a consumers premises depends on the types of loads within those premises. These loads may be linear and/or nonlinear. When linear loads are taken into consideration, any distortion in the voltage waveform is the responsibility of the supply authority. Opposite of this one is that any deviation from no load to full load at voltage waveform is the responsibility of the consumer for nonlinear loads [1]. Used simulation system and connections are shown in the next block diagram.

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The most common power quality problems, that are faced in industries, are switching transients, swells, sags, surges, extended under-voltages, outages (black and brown), harmonics and impulses with varying magnitude of the voltage at the Point of Common Coupling (PCC) [1], [2], [3].

A periodic sinusoidal waveform may be shown to be composed of the superposition of a direct component with a fundamental pure sinewave one, together with pure sinewaves as known at frequencies, that are integral multiplies of the fundamental one [4]. Others, which are different signals from fundamental one, are harmonics for electrical power systems. Shape of electrical voltages and currents are disturbed by nonlinear loads. And, harmonics effects are divided into three general categories; thermal stress, insulation stress and load disruption [5].

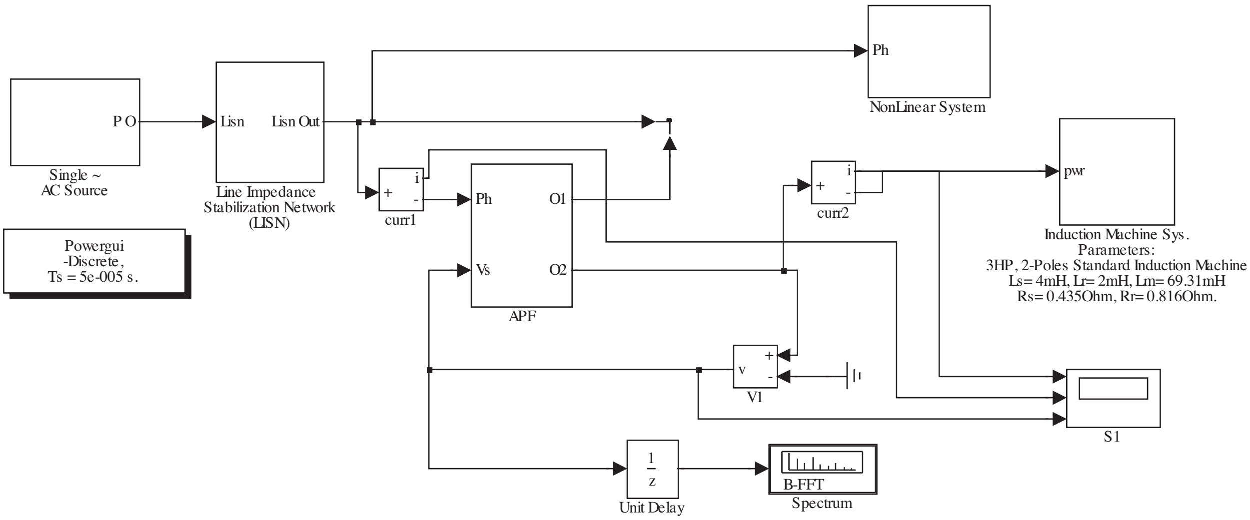

Figure 1. Used simulation power system and connections of different type electrical loads are placed in the block diagram.

If these spoiler effects are occurred, shape of these waves must be corrected to their fundamental shape again. Passive LC filters and/or APFs are used for this operation. On the other hand, passive filters have some disadvantages, such as large size, resonance problems and fixed compensation characteristics [6].

More efficient solution is utilization of APF system. The main advantages of using an APF are elimination of unwanted harmonics, power factor correction, redistribution of power to keep the system in balanced position, EMI reduction [7].

Harmonic signals and their spoiler effects on electrical motors workings are handed at graphics of motors performance parameters [8], [9]. Different types of filters are used in motor control systems for neutralizing harmonics effects on motor torque [10], [11]. And, Direct Torque Control (DTC) is used for motor torque ripple minimization [10], [12], [13]. Power systems are easily simulated using MATLAB, like other dynamic systems [7], [14], [15]. APF is placed into electrical system for saving motor torque position and saving DTC system. The first APF is controlled by classical PI-controller, which is designed by using Ziegler-Nichols technique. The filter results are used like as references for nonlinear controlled APF system [16], [17], [18].

Proposed system achievements, on each of problems, are observed with using an induction motor. DTC based induction motor is used like as an electrical load and motor output signals are examined. Unwanted effects on the load are offered before and after filters applications in graphical formations. The graphical results show that unwanted effects on the motor torque are neutralized. Same success is not verified on EMI signals. But sources of EMI signals are not used for the nonlinear controller design steps. In other words, all of these are expected results.

2. Harmonic analysis

Supply voltage of the system includes harmonics that have different operation frequencies. Figure 2 shows graphical positions of the supply voltage and harmonics positions. The supply signal is written with Fourier series and harmonic part of the signal is separated as in [5], [6].

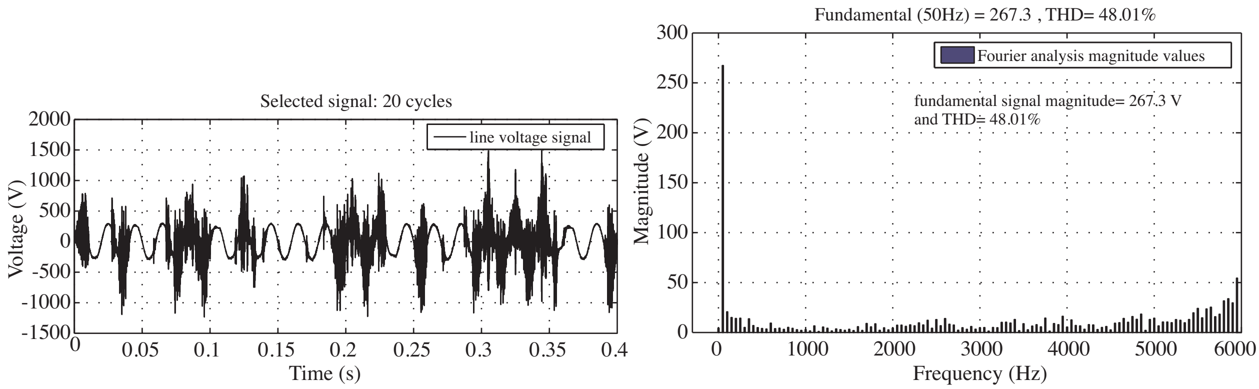

Figure 2. Supply voltage shape, which is result of nonlinear load effects.

3. Active power filter

Proposed active power filter is a voltage source-voltage controlled inverter. Total harmonic distortion (THD) is calculated by using [7], [9],

$$THD = \sqrt{V_{rms}^2 - V_{1(rms)}^2} / V_{1(rms)}. \tag{1}$$

The filter theory depends on the mathematical idea in,

$$V - V_1.sin(wt + \varphi_1) = V_0 + V_2.sin(wt + \varphi_2) + ... + V_n.sin(wt + \varphi_n). \tag{2}$$

Total of harmonic voltage is obtained by (2). Reverse of the signal is injected online to the system by using a PWM type inverter. A linear transformer (LT: 1/1) is used as an isolation element on the connection point of APF and the system. The filter is supplied by power supply system of the load. At the same time, a rectifier circuit is used to induct current of the transformer. Figure 3 shows APF and the position of its controllers with other APF system elements connections.

When switching frequency range of APF-MOSFETs is used like as reference for PWM carrier frequency, 4 kHz will be selected one. A passive filter, which has $Q_c = 1.5\ kVAr$, $V = 100\ V$, $f_{rz} \cong 82\ Hz$ and $q = \sqrt{X_C.X_L}$ ($30 < q < 100$, quality factor) parameters, is placed on output part of inverter of APF system [5]. Inductance part of the passive filter limits to APF system current. And the passive filter is set for 2 kHz upper limit of harmonics signals.

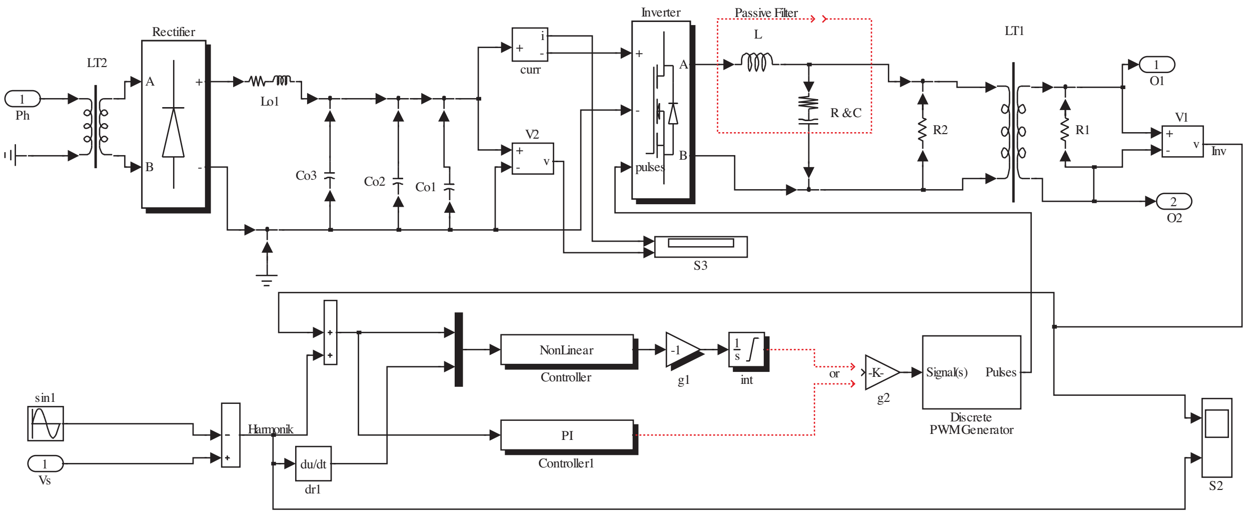

Figure 3. Elements of the APF system and used controllers that are presented with discontinuous lines, because they are used at different simulations.

Classical type PI controller is set by Ziegler-Nicholes tuning rule [17], [18]. PI controller tuning function is selected as $1.sin2\pi t$, which is get in Figure 4. Results of the design are

$$K_p = K_u/2.2 = 20/2.2 \quad and \quad \tau_i = P_u/1.2 = 1/1.2 \quad . \tag{3}$$

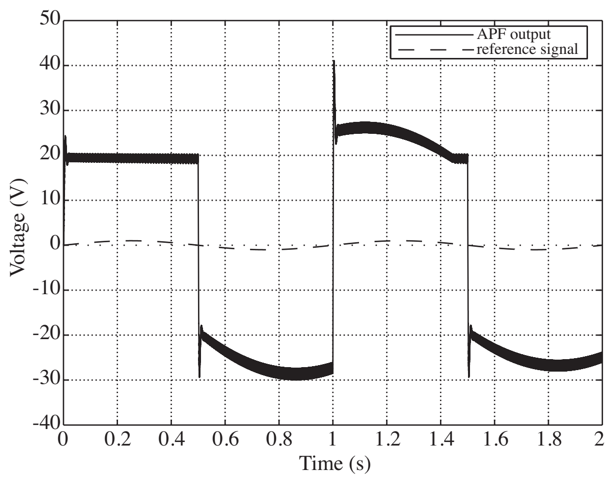

Figure 4. The PI controller design diagram.

The most basic Lyapunov function, which is $V = k.e^2/2$, is selected and exponential stability, which is $\dot{V} = -2.k.V$ is required result. Error is $e = h - o_{apf}$ and the signal is a vector variable. APF output dynamic is equal to $do_{apf}/dt = -k.e - dh/dt$. $k = K_{Umax}/2.2$ is get in nonlinear controller design from the classical controller design. When APF output dynamic is used, $V(x,t) > 0 \ \forall x, t \neq 0$ exponential stability is obtained [19], [20].

4. Direct torque control algorithm

In order to analyze a DTC system, induction machine model is get in the general reference frame.

$$\overline{V}_s^g = R_s.\bar{i}_s^g + \frac{d\overline{\psi}_s^g}{dt} + j.w_g.\overline{\psi}_s^g \quad and \quad 0 = R_s.\bar{i}_r^g + \frac{d\overline{\psi}_r^g}{dt} + j.(w_g - w_r).\overline{\psi}_s^g, \tag{4}$$

$$\overline{\psi}_s^g = L_s.\bar{i}_s^g + L_m.\bar{i}_r^g \quad and \quad \overline{\psi}_r^g = L_r.\bar{i}_r^g + L_m.\bar{i}_s^g. \tag{5}$$

Where $\overline{V}_s$ is stator supply voltage, $\bar{i}_s$ and $\bar{i}_r$ are stator and rotor currents, w_g is general reference speed, w_r is rotor speed. R_s, R_r are stator and rotor resistances $\overline{\psi}_s^g$ and $\overline{\psi}_r^g$ are stator and rotor flux linkages. The superscript "g", which is in equations, points out to reference frame [12], [21].

Mechanical dynamics of an induction motor are

$$T_e = \frac{3}{2}.\frac{p}{2}.Im(\overline{\psi}_s^g.\bar{i}_s^g) \quad and \quad J.\frac{dw_m}{dt} = J.\frac{2}{p}.\frac{dw_r}{dt} = T_e - T_{load}. \tag{6}$$

T_e is motor torque, J is inertia moment of system and T_{load} is torque of load [12]. DTC system of inverter fed induction motor is carried out hysteresis control of magnitude of stator flux and magnitude of electromagnetic torque. The controller selects one of the six non-zero and two zero voltage vectors of inverter that vectors are get in Figure 5 [14].

$$\Delta T_e = T_{eref} - T_e \quad and \quad \Delta\overline{\psi}_s^g = \overline{\psi}_{sref}^g - \overline{\psi}_s^g \tag{7}$$

ΔT_e and $\Delta\overline{\psi}_s^g$ point out to torque and flux errors, respectively. The switching vector selection depends upon that the errors must be taken into hysteresis band. Vectors of $\overline{V}_s^g$ are determined and output value of the inverter is easily calculated by using (8) [14].

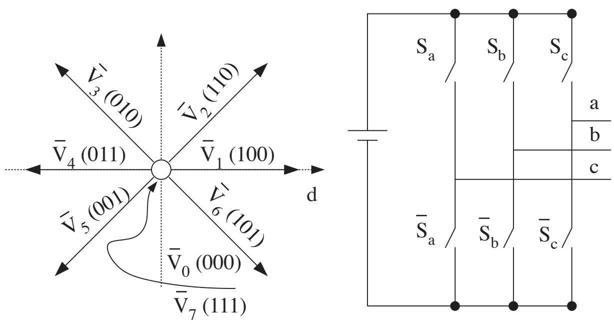

Figure 5. Classical inverter and its output vectors, that are used by DTC algorithm.

$$\overline{V}_s^g = \frac{2}{3}.V_{dc}.(S_a + e^{j.\frac{2.\pi}{3}}.S_b + e^{j.\frac{4.\pi}{3}}.S_c) \tag{8}$$

By selecting appropriate voltage vector of inverter, stator flux is rotated to desired frequency (w_s) that is inside a specified band. When stator ohmic drops are neglected, stator flux dynamic is calculated by using

$$\Delta\overline{\psi}_s^g = \overline{V}_s^g.\Delta t. \tag{9}$$

Eqn. 6 is a sinusoidal function of γ on motor torque and γ is the angle between stator and rotor fluxes. When the angle is adapted by using vector selection, required stator flux and electromagnetic torque are obtained [15].

$$\overline{\psi}_s^s = \int (\overline{V}_s^s - \overline{i}_s^s . R_s) dt \quad and \quad T_e = \frac{3}{2} . P . (\psi_{ds}^s . i_{qs}^s - \psi_{qs}^s . i_{ds}^s). \tag{10}$$

$\overline{V}_s^s$ and $\overline{i}_s^s$ are measured stator voltage and stator current signals. $\overline{\psi}_s^s$ is accounted stator flux vector. T_e vector angle and $\overline{\psi}_s^s$ vector angle are enough for voltage vector selection.

5. Supply voltage positions

Time of verified simulations is 5.0 seconds and nonlinear load connected to power system is between 0.6-3.0 seconds. Nonlinear load effects and filters effects are got in Figure 6 are between 1.8-2.8 seconds. The harmonic

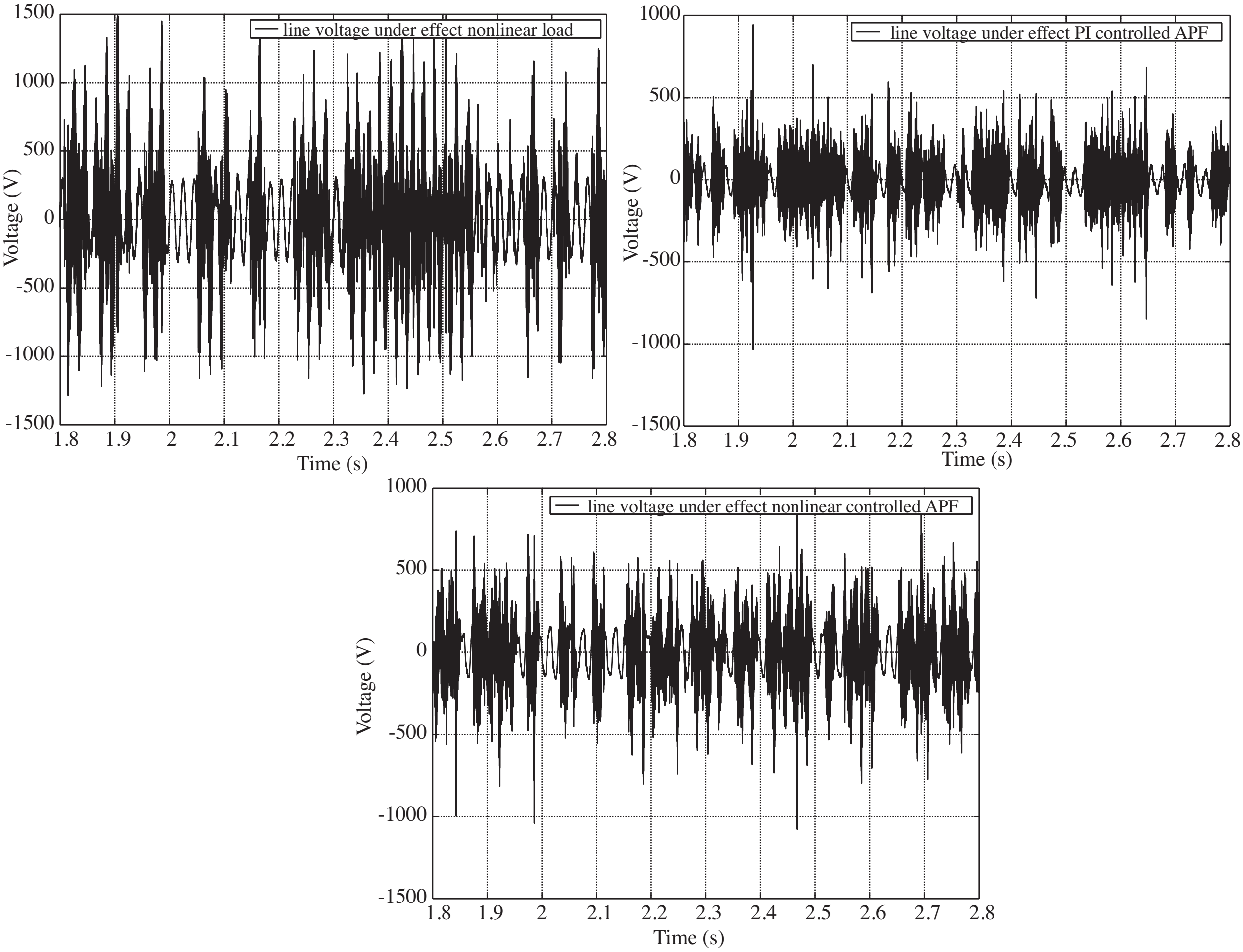

Figure 6. Effects of nonlinear load, nonlinear load with PI controlled APF and nonlinear load with nonlinear controlled APF systems on power system voltage signal, respectively.

signals, which are taken to their positions by nonlinear load effects, are on other parts of the system. THD value is equal to $\sim 48/100$. Both of APF systems take down THD value to $\sim 21/100$. But Fourier Analysis results show that nonlinear controlled APF supplies 80 V upper magnitude value, that is magnitude of fundamental frequency than PI controlled APF. Both of APF systems effect to harmonics which have frequency values up to 6 kHz in a limited value. Main reason of these limits is the passive power filter. APF systems are not designed for reducing the THD value under IEEE, IEC, EN or NORSOK limits [5].

6. Effects on system parameters of the motor

Motor torque positions are got for 3.0 Nm reference in Figure 7. The torque has a wavy graphical changing in adding time part of nonlinear load. Limit values that are 0-4.8 Nm of the graphic are greater than 2-4 Nm that are limits of nonharmonic included power supply system. When APFs are added to power system in order, graphical position of motor torque is taken into normal limits.

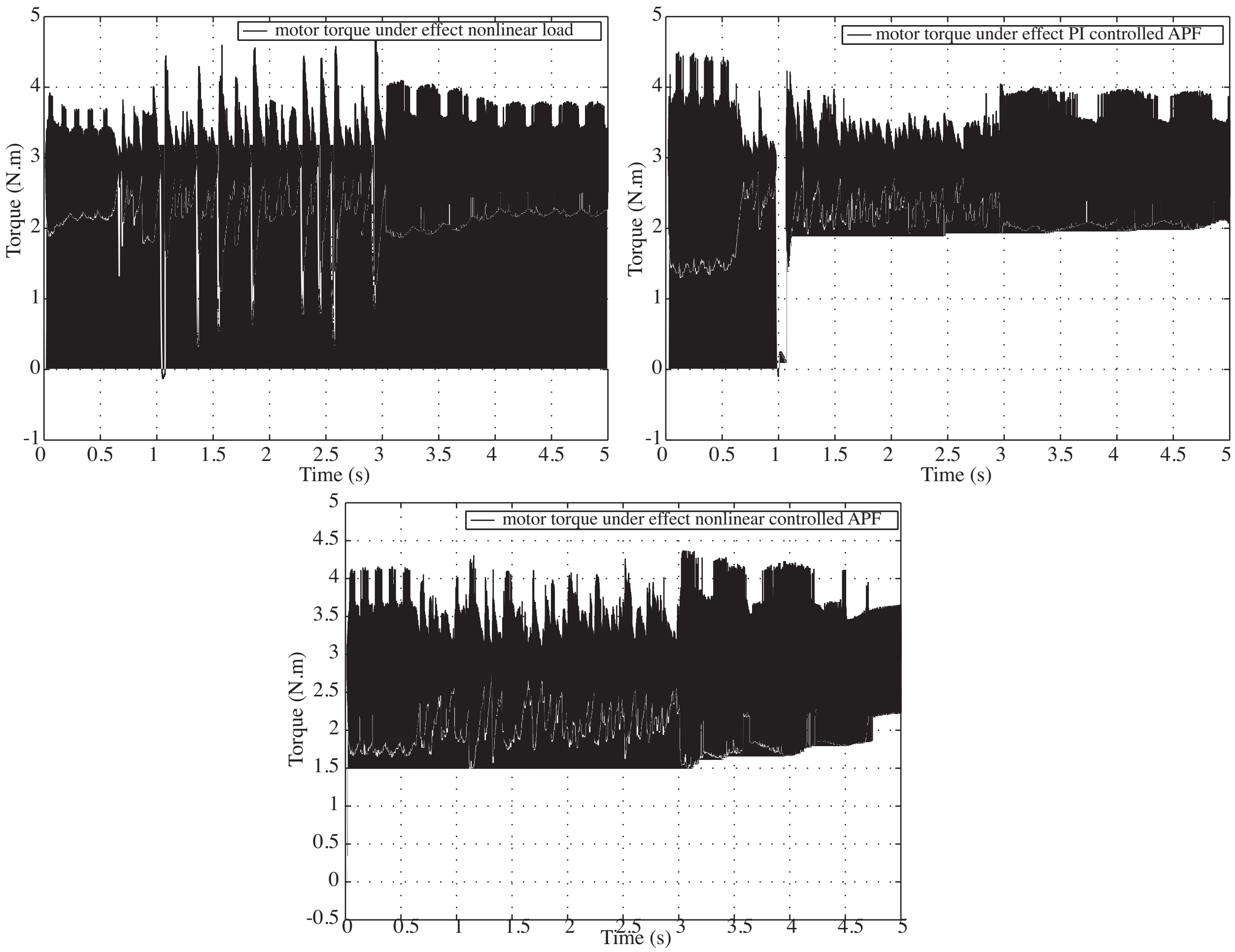

Figure 7. Effects of nonlinear load, nonlinear load with PI controlled APF and nonlinear load with nonlinear controlled APF systems on motor torque position are get in respect.

A speed control block is not added into the control system. But supply voltage harmonics effect to motor speed. And responses of both of APF systems to the harmonics put forward to important changes on motor speed. All the speed positions are placed in next figure and linear change is obtained by only nonlinear controlled APF.

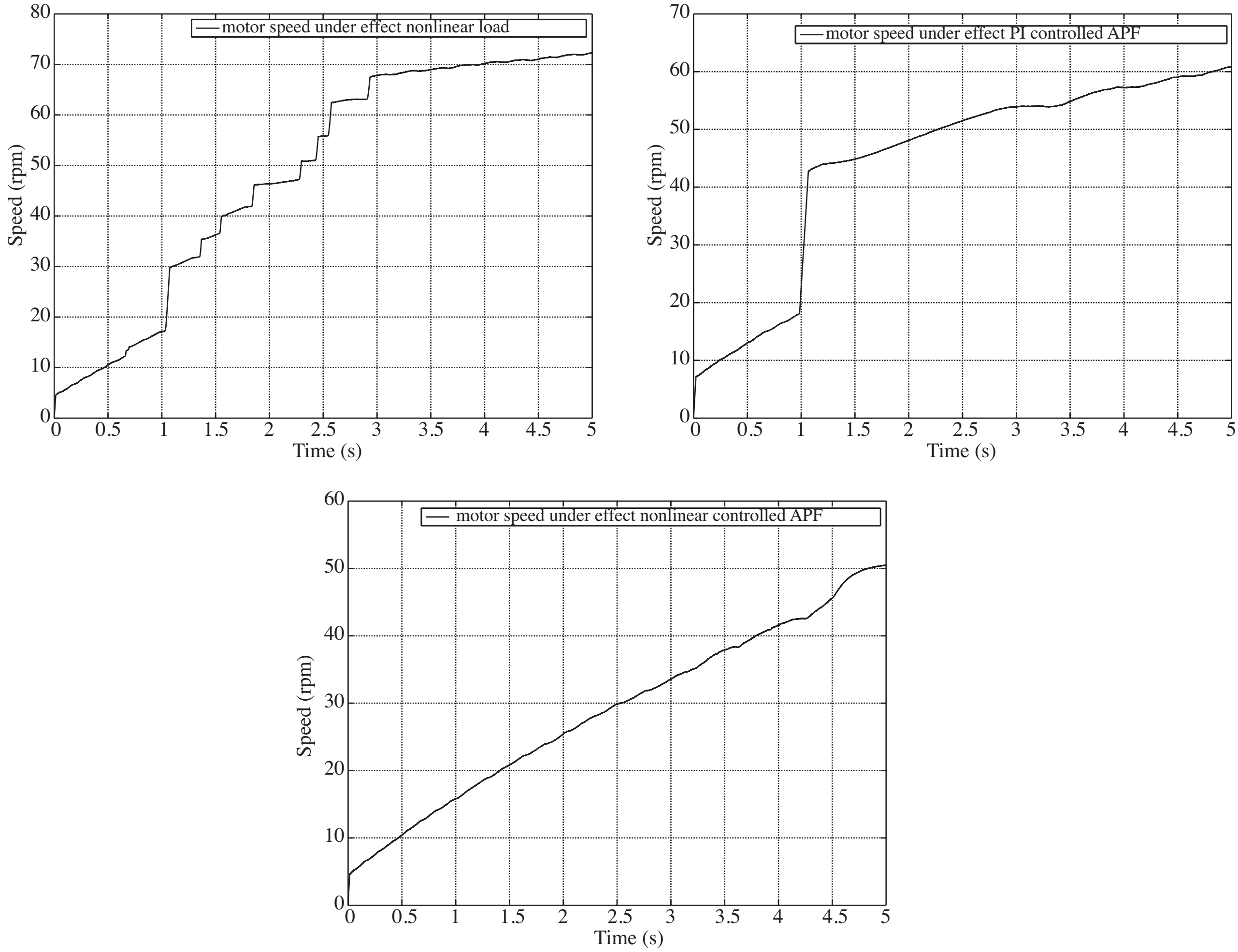

Figure 8. Effects of nonlinear load, nonlinear load with PI controlled APF and nonlinear load with nonlinear controlled APF systems on motor speed are placed in graphics, respectively.

Like other output parameters of motor, stator flux is disturbed by voltage harmonics. Reference flux value is selected 0.3 Wb in DTC system. But flux magnitude of motor is reduced to 0.2 Wb in milliseconds. These flux waves are cleared by nonlinear controlled APF. The filter response to the harmonics is located on the power system. Cleared phase currents are obtained by cleared power system. Cleared flux signals, that are in Figure 9 are obtained by cleared phase currents. Finally, cleared motor torque is obtained by union of these signals.

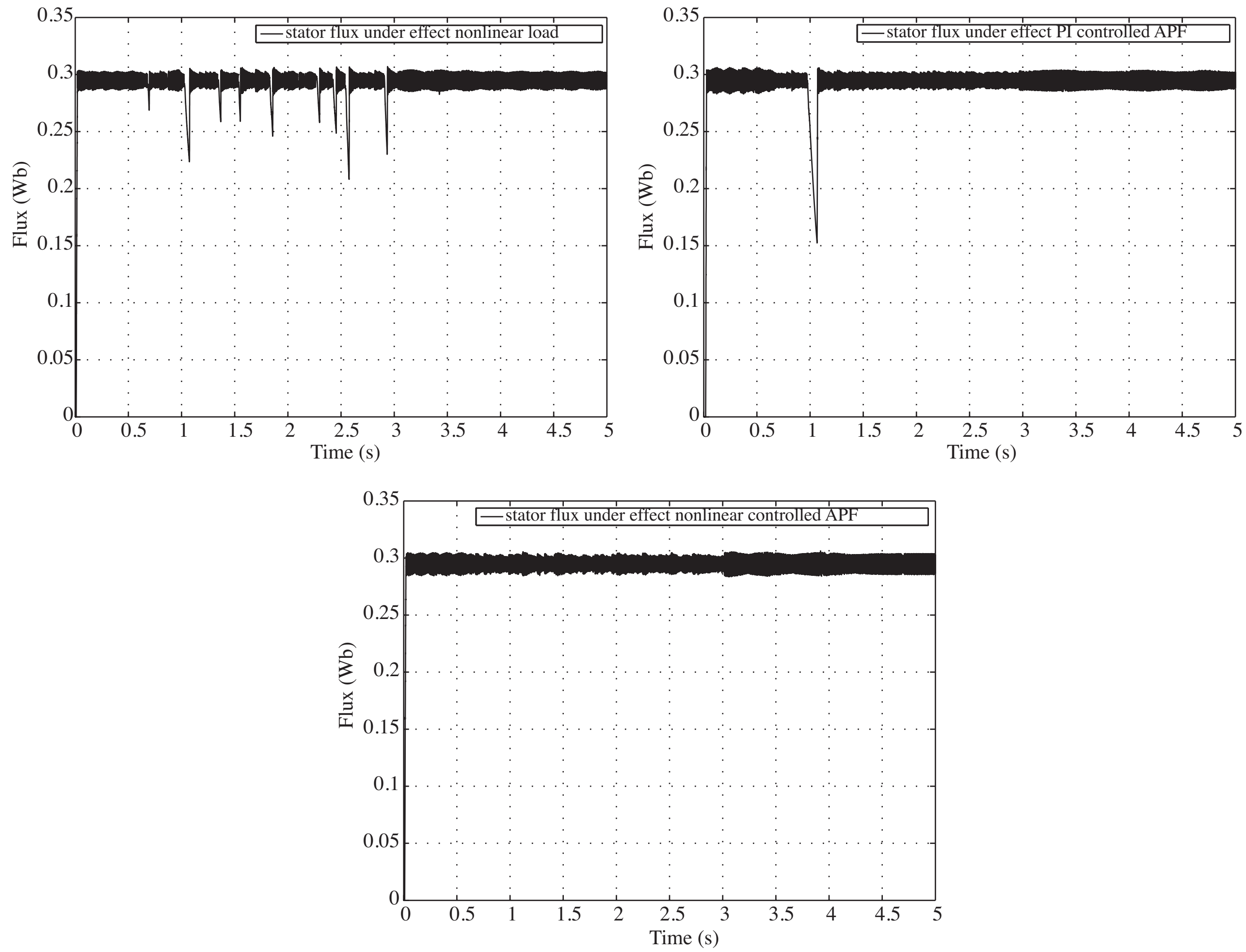

Figure 9. Effects of nonlinear load, nonlinear load with PI controlled APF and nonlinear load with nonlinear controlled APF systems on stator flux are get in respect.

7. Results and conclusion

APF position is selected as between power line and motor control system. In this condition, APF adapts automatically for new power line signals. Defects on stator flux and on motor torque are restored by voltage source-voltage controlled inverter. A classical control technique is enough for this restoring operation. But connection time of nonlinear load is considered, nonlinear controller is more successful. It means that motor system is not informed of nonlinear load and its effects. Similar success is obtained on motor speed. Because linear changes of motor speed is put forward by only nonlinear controlled APF. Nonlinear controller design theory opens a road for taking new parameters into control system. In this paper, dynamics of error signal are taken into nonlinear controller and extra successful positions are obtained. Passive filter, which is placed inside of APF, prevents to effects on EMI signals. EMI signals' value is 45 dB before and after APF. The result is that new filter position with nonlinear controlled APF shows desired performance on motor parameters. Variable conditions do not prevent to this performance. This one is offered by using PI controlled APF and verified simulations.

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