On-Line Search Based Pulsating Torque Compensation of a Fault Mode Single-Phase Variable Frequency Induction Motor Drive

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Abstract—Improved reliability and fault tolerant operation of inverter-fed variable frequency ac drives are very important for critical industrial applications. The paper describes variable frequency, variable voltage operation of a three-phase induction motor drive in single-phase mode for inverter fault conditions, such as open base drive and device short circuit. The detailed mathematical analysis of the machine in single-phase mode indicates that odd harmonic voltages of appropriate magnitude and phase can be injected at the machine terminal to neutralize the large low-frequency pulsating torques so as to permit smooth drive operation. The magnitude and phase angle of the desired harmonic voltages have been derived theoretically. However, to eliminate the parameter variation effect and operating point dependencies, a general purpose search algorithm has been proposed in the paper which fabricates the desired harmonic voltages on real time basis. The search algorithm was initially exercised manually on a simulated drive system to prove its validity, and then tested extensively on a volts/hertz controlled 3-hp drive system in the laboratory. The on-line search algorithm along with estimation and control related to the project was implemented with C language on a TMS320C30 digital signal processor board. The extensive laboratory investigation shows that the proposed search algorithm performs well and successfully eliminates low-frequency pulsating torques not only in a steady-state condition but also during slow acceleration and deceleration of the drive. The search algorithm is perfectly general and can be easily extended to other induction motor drives.

I. INTRODUCTION

O
PEN loop volts/hertz speed control of an induction motor with a voltage-fed PWM inverter is widely used for various industrial applications. Improved reliability and fault tolerant operation of the drive are very important in many critical applications. Redundancy and conservative design techniques, although at higher cost, have been widely used to improve the reliability. In case of inverter fault, such as base drive open or device short circuit; the protection system is normally designed to shut down the drive ignoring its consequence on the process control. For a fault in a device, it is possible to isolate the faulty inverter leg and continue operation of the three-phase motor in a single-phase mode [2], [3], [5] with reduced torque, if the load condition permits. Single-phase operation of three-phase motors has been widely studied in literature. In single-phase mode, the machine generates a large second harmonic pulsating torque which is practically harmless with 60-Hz power supply because of effective inertia filtering. With inverter-fed variable frequency power supply, the low pulsating torque frequency will cause speed jitter and possible mechanical resonance which are unacceptable. A solution to this problem for a vector-controlled induction motor drive is proposed in [4]. However, the scheme has a limitation, because it considers neutral connection of the machine. A standard isolated neutral wye-connected or delta-connected machine cannot use this technique. Besides, the additional penalty is that the dc link filter capacitor needs to be overdesigned (by a factor of 5 to 10) because a large fundamental frequency neutral current is returned to the center point of the split filter capacitor. A method of neutralizing low-frequency pulsating torque in a standard isolated neutral machine in a single-phase mode has been described by the authors [1]. In this scheme, precomputed odd harmonic voltages at an appropriate magnitude and phase angle are injected at the machine terminal in order to suppress low-frequency pulsating torques. However, because of parameter variation and operating point dependence problems, the performance of the pulsating torque suppression algorithm is somewhat inferior.

The paper describes a general purpose search algorithm that fabricates the desired harmonic voltage magnitudes and phase angles on real time basis at the machine terminal in order to suppress the low-frequency pulsating torques. The algorithm has the advantages that it is perfectly general, independent of machine parameters and the operating condition, and therefore, can be easily extended to any drive.

II. PULSATING TORQUE SUPPRESSION PRINCIPLE

The principle of pulsating torque suppression will be discussed in the beginning. Fig. 1 shows the power circuit of a volts/hertz controlled induction motor drive that operates in
fault mode single-phase condition. The switch $S_1$ indicates the open gate drive fault and the switch $S_2$ indicates the device short-circuit fault. It has been shown [2] that for these faults, it is not safe to operate the drive even after inhibiting the device $Q_4$. The switch $S_3$ is to be opened to completely isolate the faulty leg and operate the drive in the single-phase mode.

The symmetrical component method was used to analyze the machine behavior at any harmonic frequency. The analysis yields steady-state performance of the drive system under usual assumptions of magnetic linearity and sinusoidal airgap flux. In a practical machine, however, the machine parameters, particularly the magnetizing inductance of the machine, depend heavily on the saturation level. Therefore, in the following analysis, the saturated value of magnetizing inductance on the basis of linear segments will be used. Fig. 2 shows the positive sequence and negative sequence equivalent circuits of the machine at $k$th harmonic. The stator voltages and currents, as indicated in the figure, are related to the supply voltage and current, respectively, by the following equations:

$$V_k = j\sqrt{3}(V_{uk} - V_{pk})$$  

(1)

$$I_k = -j\sqrt{3}I_{spk} = j\sqrt{3}I_{snk}$$  

(2)

where $V_k$ = per phase supply voltage and $I_k$ = line current at $k$th harmonic. Fundamental frequency behavior of the machine can be studied by substituting $k = 1$ in Fig. 2. The average torque $T_e$ and second harmonic torque $T_{e2}$ can be given, respectively, by the following equations:

$$T_e = \text{Im}(I_{sp1}I_{r1} + I_{sp1}I_{r2})$$  

(3)

$$T_{e2} = |I_{sp1}I_{r1} + I_{sp1}I_{r2}|$$  

(4)

where the symbol * indicates that the variable is a complex conjugate and Im indicates an imaginary part of the expression. The large magnitude of second harmonic pulsating torque will cause speed jitter and may cause a mechanical resonance problem.

To reduce the effect of pulsating torque, a novel algorithm was proposed [1] that increases the frequency of torque pulsation while maintaining its magnitude constant. At higher frequency, a nominal drive inertia can attenuate the corresponding speed ripple considerably. The algorithm injects odd harmonic voltages at an appropriate phase angle with respect to the fundamental voltage to neutralize the lower order harmonic torques. In fact, the harmonic neutralization scheme works directly with a current-controlled system, as explained in Fig. 3. Here, a third harmonic current with an equal magnitude of fundamental current is injected at an appropriate phase angle ($\theta_3$) to neutralize the second harmonic torque. However, as a consequence, a fourth harmonic torque of equal magnitude appears at the output. Note that the peak current increases as a result of this injection. The pulsating torque frequency can be shifted to a higher value in the spectrum by injecting other odd harmonic currents, such as fifth, seventh, etc. In general, it can be shown that harmonic currents up to order $2k + 1(k = \text{integer})$ can be injected to eliminate up to 2$k$th order harmonic torques.
The general expression of instantaneous developed torque in the presence of stator current harmonics up to the order \(2k + 1\) can be derived from Fig. 2 and given as

\[
t_c = 3L_r \text{Im} \sum_{l=1}^{2k+1} \sum_{m=1}^{2k+1} [I_{spl}^* I_{rpm}^* e^{j(l-m)\omega_c t} \\
+ I_{sn}^* I_{rpm}^* e^{-j(l+m)\omega_c t} + I_{spl}^* I_{rn} e^{j(l+m)\omega_c t} + I_{sn}^* I_{rn} e^{-j(l-m)\omega_c t}]
\]  

(5)

where \(\text{Im}\) means the imaginary part of the expression, and all the symbols are as indicated in Fig. 2. In (5), the effect of harmonic fluxes generated by the corresponding harmonic currents are ignored for simplicity. The explicit expressions of individual harmonic torques can be written from (5) and then equated to zero to derive the corresponding expressions for harmonic currents. The general expression for \(k\)th harmonic injected current can be derived as

\[
I_k = I_1 e^{j(k-1)\theta}
\]  

(6)

where

\[
\theta = \frac{\pi}{2} - \tan^{-1} \left( \frac{\omega_{slp} I_r}{R_r} - \tan^{-1} \left( \frac{2\omega_c - \omega_{slp}}{R_r} \right) \right). 
\]  

(7)

If the fundamental line current is given as

\[
i_1(t) = \sqrt{2} I_1 \cos(\omega_c t + \alpha)
\]  

(8)

then the \(k\)th order \((k = 1, 3, 5, \ldots)\) harmonic current expression can be given by

\[
i_k(t) = \sqrt{2} I_1 \cos(k\omega_c t + k\alpha + (k-1)\theta)
\]  

(9)

where \(\alpha\) is the arbitrary phase angle. Note that the harmonic current magnitude is the same as that of the fundamental. The total machine current is given by the superposition principle as follows:

\[
t(t) = \sum_{k=1,3,5,\ldots} i_k(t).
\]  

(10)

Equations (8)–(10) define the harmonic torque elimination algorithm in terms of injected harmonic currents. The algorithm can be implemented directly on an inverter with instantaneous current control. However, for a volts/hertz controlled inverter, the equivalent voltage equations are to be derived. From Fig. 2, the supply phase voltage can be related to the corresponding line current at \(k\)th harmonic by the expression

\[
V_k = I_k (Z_{pk} + Z_{nk})
\]  

(11)

where \(Z_{pk}\) and \(Z_{nk}\) are the total stator impedances at positive sequence and negative sequence, respectively. If the fundamental supply phase voltage is given by

\[
v_1(t) = \sqrt{2} V_1 \cos(\omega_c t)
\]  

(12)

then the \(k\)-th harmonic supply voltage expression can be given as

\[
v_k(t) = \sqrt{2} V_k \cos(k\omega_c t + \phi_k)
\]  

(13)

where

\[
\phi_k = \theta_{ck} - k\theta_{z1} - (k - 1)\theta_C\]

(14)

\[
\theta_{ck} = \angle(Z_{pk} + Z_{nk})
\]  

(15)

\[
\theta_{z1} = \angle(Z_{p1} + Z_{n1})
\]  

(16)

and

\[
\theta_c = \tan^{-1} \left( \frac{\omega_{slp} L_r}{R_r} \right) + \tan^{-1} \left( \frac{2\omega_c - \omega_{slp}}{R_r} \right).
\]  

(17)

The corresponding supply voltage expression and that including the injected harmonics are given respectively as

\[
V_k = \frac{|Z_{pk} + Z_{nk}|}{|Z_{p1} + Z_{n1}|} V_1
\]  

(18)

\[
v(t) = \sum_{k=1,3,5,\ldots} v_k(t).
\]  

(19)

For a given operating slip \(\omega_{slp}\), the compensating harmonic voltages can be computed as functions of fundamental frequency \(\omega_c\) and stored in the form of look-up tables. This method of implementation was discussed in [1]. Although somewhat simple to implement, this approach has several disadvantages: 1) The machine parameters are required to be known accurately; performance of the algorithm degrades as the machine parameters vary during the drive operating condition; 2) the operating slip \(\omega_{slp}\) of the machine is required to be known; and 3) the equations do not include the effect of harmonic fluxes and accurate inductance saturation models.

III. PULSATING TORQUE SUPPRESSION BY ON-LINE SEARCH METHOD

An on-line search method of pulsating torque suppression will be presented that solves the above problems. Since it does not require knowledge of machine parameters, it can be applied to a general purpose drive system where the machine parameters are unknown. The proposed algorithm estimates the harmonic torque components in an experimental drive system and then attempts to eliminate the lower order harmonic torques by injecting the harmonic voltages of appropriate magnitude and phase angle.
Assume for simplicity that third harmonic voltage in addition to the fundamental voltage is applied to the machine terminal. The amplitude of second harmonic torque under this condition in terms of currents can be obtained from (5) and written in simplified form as follows:

\[ T_{r,2} = L_n I_3 (\chi_{p1} + \chi_{n1} - \chi_{p3} - \chi_{n3}) - I_1 (\chi_{p1} + \chi_{n1}) \]  

(20)

where

\[ \chi_{p,3} = \frac{I_{p,3}}{I_{p,3}} \quad \chi_{n,1} = \frac{I_{n,1}}{I_{p,3}} \]  

(21)

(22)

The terms \( I_3 \) and \( I_1 \) are the third harmonic and fundamental line currents, respectively. Using (11), the above equation can be expressed in terms of voltages as follows:

\[ T_{r,2} = L_n |V_3 - OP||Q| \]  

(23)

where

\[ OP = \frac{(Z_{p3} + Z_{n3})(Z_{p1} + Z_{n1})(\chi_{p1} + \chi_{n1})}{(Z_{p3} + Z_{n3})^2(\chi_{p1} + \chi_{n1} + \chi_{p3} - \chi_{n3})} V_1 \]  

(24)

and

\[ Q = \frac{(\chi_{p1} + \chi_{n1} - \chi_{p3} - \chi_{n3})}{(Z_{p3} + Z_{n3})(Z_{p1} + Z_{n1})} V_1 \]  

(25)

The terms \( V_3 \) and \( OP \) can be considered as voltage vectors. Note that \( OP \) and \( Q \) are independent of third harmonic voltage, and in fact, are constants for a given fundamental voltage and load torque condition. Therefore, (23) indicates that the amplitude of second harmonic torque is proportional to the magnitude of the vector difference between the injected third harmonic voltage \( V_3 \) and the fixed vector \( OP \). The above situation is explained graphically in Fig. 4 where the \( XY \) plane contains the voltage vectors, and the magnitude
of second harmonic torque is represented in the Z-axis. The inverted cone SRP is standing vertically with its apex P touching the XY plane. Any vertical projection from the surface of the cone represents the second harmonic torque as a scalar function of the third harmonic voltage vector. In the figure, as shown, the initial voltage vector \( V_3 \) at angle \( \phi_3 \) (represented by \( OM \)) generates the harmonic torque \( MM' \), but perfect compensation of the harmonic torque is achieved if \( V_3 = OP \). The search algorithm initially changes the phase angle \( \phi_3 \) so that the \( V_3 \) vector rotates along the arc \( MQ \) and coincides with the \( OP \) vector. In this phase angle search, the torque attenuates from \( MM' \) to \( QQ' \). Then, the \( V_3 \) magnitude is extended to be equal to \( OP \) so that the harmonic torque reduces to zero following the locus \( QP \), as shown. Figures similar to Fig. 4 can be used to explain the attenuation of fourth, sixth, etc., harmonic torques.

In the practical implementation of the search algorithm, it is important to search the phase angle first and then the magnitude of the voltage vector. This can be explained as follows: From Fig. 4, it can be shown that

\[
T_{e2} \propto |PM|.
\]

(26)

It can also be shown that the fourth harmonic torque \( T_{e4} \) is directly related to the magnitude of the \( V_3 \) vector, i.e.,

\[
T_{e4} \propto |OM|.
\]

(27)
The total rms pulsating torque \( T_{eh} \) is then given by
\[
T_{eh} = \sqrt{\frac{T_{c2}^2 + T_{c3}^2}{2}} \propto \sqrt{|PM|^2 + |OM|^2}. \tag{28}
\]

If the magnitude search is considered first, the third harmonic voltage vector in Fig. 4 will grow from \( OM \) to \( ON \), causing the rms pulsating torque much higher than the uncompensated value. On the other hand, with the phase angle search in the beginning, the rms pulsating torque will always remain lower than the uncompensated value. In summary, the overall search algorithm can be described as follows:

- Estimate the second harmonic torque component \( T_{c2} \) by Fourier analysis of the total estimated instantaneous torque (see Fig. 6).
- Inject an initial third harmonic voltage and start increasing its phase angle. If \( T_{c2} \) magnitude decreases, then continue search in the same direction. If, on the other hand, \( T_{c2} \) increases in magnitude then decrease the phase angle and continue search so that \( T_{c2} \) decreases in steps.
- Then, follow the above step for third harmonic voltage magnitude until \( T_{c2} \) attains below a threshold value. Below this threshold, the effect of fourth harmonic pulsating torque generated by the injected third harmonic voltage becomes more dominant than the residual second harmonic torque. Consequently, attenuation of second harmonic torque is suspended temporarily and the search algorithm is activated to attenuate the fourth harmonic torque.
- Repeat all the above steps for fourth and sixth harmonic torques by iterating respectively the fifth and seventh harmonic voltages with the corresponding phase angles.
- Once all the harmonic torque components (second, fourth, and sixth) are below the corresponding threshold values (or the sixth harmonic torque attenuation was prematurely abandoned due to inverter current limit which will be explained later), the search algorithm loop starts again with a lower step size. The search algorithm always remains active during the single-phase operation mode of the drive. Fig. 5 shows the flowchart for the search algorithm. Although it shows attenuation of the lowest three harmonic torques, it can be extended in principle for higher harmonic torques also.

IV. EXPERIMENTAL IMPLEMENTATION OF ON-LINE SEARCH ALGORITHM

The search algorithm, as described above, was implemented on a commercial open loop volts/hertz controlled 3-hp laboratory drive [10] with a PWM IGBT inverter, and performances
were extensively studied. Fig. 6 shows a block diagram of the drive control system. The controller is based on TMS320C30 type digital signal processor board and the total software was implemented with C language. The original SPWM modulator of the drive is replaced by a custom-designed dedicated hardware modulator where the analog modulating voltage waves were obtained from D/A converters. The carrier frequency for modulation was fixed at 15 kHz. The drive system originally operates in three-phase (switch $S_3$ closed) variable frequency variable voltage mode when the speed command generates the appropriate sinusoidal modulating voltages. The machine terminal voltages and currents are sensed, passed through a low-pass filter (LPF) and then fed to the DSP for estimation of torque. At steady-state three-phase operation mode, the load torque (equal to the developed torque) is estimated which will determine the optimum fundamental voltage ($V_1$) to be applied to the machine in single-phase mode. It was shown [2] that in single-phase mode, the machine fundamental voltage should be programmed as a function of the load torque at a given frequency in order to minimize the line current and reduce the amplitude of pulsating torque. The controller stores the fundamental voltage-frequency equations as a function of load torque in the form of a look-up table, as indicated in the figure.

At transition to the single-phase mode, the voltage $V_1$, as calculated above, is applied to the drive, initially assuming that the load torque and fundamental frequency remain the same. Then, the search algorithm starts working. The torque estimation program estimates the instantaneous torque and then calculates the average torque ($T_e$) and harmonic torques ($T_{e2}$, $T_{e4}$, and $T_{e6}$) by Fourier analysis, and feeds the latter information to the search algorithm, as shown. At any instant, $V_1$ is corrected by the command speed and the estimated $T_e$ signals. The search algorithm determines the incremental harmonic voltage and phase angle control signals and helps to generate the nonsinusoidal modulation waveform for the inverter, as shown in Fig. 6. During operation of the search algorithm, the machine rms and peak currents are always monitored to be sure that they do not exceed the safe limits.

As mentioned before, the search for higher harmonic torque attenuation is suspended as soon as either of the currents tend to exceed the limit. Evidently, the search algorithm does not require any machine parameter information, and therefore, can be applied to any drive.

In practical implementation of the search algorithm, a few issues, such as choice of phase angle quadrant for initial harmonic voltage vector, speed of convergence, and local minima problem became important. The initial injected harmonic voltage vector is to be placed in the correct phase quadrant by quadrant search, and then phase angle incrementation should begin in order to avoid unduly long angle search time. The speed of convergence depends on the search step size. A larger step size enhances this speed but causes excessive oscillation in steady state. In the present project, the stages $S_1$, $S_2$, and $S_3$ in Fig. 5 use a large step size whereas the looping stages $S_4$, $S_5$, and $S_6$ use a small step to solve the above problem. The local minima in harmonic torques constitute a complex problem which is caused by various nonidealities, such as inverter dead-time effect, machine saturation, etc. With local minima, oscillation occurs in a suboptimal region and prevents attaining the desired global minimum point. In order to avoid this problem, the search in each case is conducted for the second time in the adverse direction in order to assure crossing the hill of the local minima.

The experimental drive system in the laboratory was coupled to a dynamometer load, and square-law load characteristics were emulated. In the beginning, the preliminary search algorithm was exercised manually on a simulated drive to prove its validity. Then, the control software was developed and exercised manually in the experimental single-phase drive system. After validation, the fully operational software was activated on the experimental single-phase drive system. The performance of the search algorithm seemed to be very well. Fig. 7 shows the attenuation of second harmonic torque as the search algorithm manipulates the phase angle and magnitude of the third harmonic voltage. The initial voltage of 0.02 pu was injected at phase angle $\phi_3$ and then the angle search began. No quadrant search was needed in this case because
it was known \textit{a priori} that the optimum angle will always lie in the first quadrant. As indicated in the figure, the magnitude search starts after the phase angle search and is continued until the torque falls below the threshold value. Fig. 8 shows the attenuation of fourth harmonic torque by injection of fifth harmonic voltage. Because of uncertainty of the initial quadrant, a quadrant search began between the first and second quadrants, but it was found that the first quadrant is optimal in this case. The rest of the search procedure is similar to Fig. 7. Fig. 9 shows the similar search procedure for the sixth harmonic torque. In this case, the quadrant search was made among the first, second, and third quadrants, but the first quadrant was found to be optimal. During the magnitude search, it was found that the peak current exceeds the limit at time $t_{el}$ (see Fig. 9(c)), and therefore, the voltage $V_7$ is backed off to restore the current within the safe limit. The corresponding adverse effect on $T_{el}$ is noticeable in Fig. 9(a). Note that the search procedure for Figs. 7–9 was conducted sequentially although they are shown on the same time base. Fig. 10 shows the steady-state drive performance without pulsating torque compensation and at the rated flux where the large second harmonic torque is evident. Fig. 11 shows the corresponding performance at programmed flux with harmonic torque compensation. The large second harmonic torque has been completely suppressed, and instead, sixth and eighth harmonic torques appear at reduced magnitude which give low speed ripple because of inertia filtering. As mentioned before, higher order harmonic voltages can be injected to shift the pulsating torque to higher order in the spectrum if permitted by the current limits of the inverter. As indicated in Fig. 11(c), $T_{el}$ could not be significantly attenuated because of the current limit. After successful exercise of the search algorithm in steady state, the performance of the drive was tested for limited acceleration and deceleration. Figs. 12–14 show the compensation characteristics when the drive accelerates from 10 Hz to 20 Hz at the rate of 0.5 Hz/s. Similar tests were conducted also for deceleration of the drive and performance was found to be equally satisfactory. The limited acceleration/deceleration performance in addition to steady-state operation at reduced torque is particularly important
for transportation type applications (high inertia load), such as electric vehicles and subway trains where the vehicle or train can be safely brought back to the garage with the faulty inverter. Obviously, designing the inverter-machine conservatively with higher current limit can give better pulsating torque attenuation and higher acceleration/deceleration characteristics.

V. CONCLUSION

In this paper, an on-line search algorithm for neutralization of low-frequency harmonic torques for fault mode single-phase operation of a variable frequency variable voltage induction motor drive is described. The harmonic torque elimination has been achieved by injection of odd harmonic voltages at an appropriate magnitude and phase angle which were derived by theoretical analysis. The advantages of the on-line search method is that it is perfectly general and can be applied to any drive without information of machine parameters and operating conditions. The algorithm was implemented on an experimental laboratory drive system with a TMS320C30 type DSP-based controller. The performances at steady state and at limited acceleration/deceleration were found to be excellent. A more effective harmonic torque suppression is possible with higher current limit of the inverter. Although the principle has been applied to a conventional volts/hertz controlled induction motor drive, it can also be applied to a vector-controlled drive by permitting the drive to operate in volts/Hz control mode in faulty condition. The scheme is particularly attractive for industrial applications with high inertia load.

REFERENCES


KASTHA AND BOSE: ON-LINE SEARCH BASED PULSATING TORQUE COMPENSATION


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