AC Magnetic Phase Balancing -- A Method of Power Quality Control

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Abstract -- **This paper reviews the literature since 1992 when an AC, Magnetic, Phase Balancing Device was first described. The more precise data from earlier papers are discussed and several probable physical mechanisms are described through which the phase balancing device effects power quality. The purpose of this review is to establish connection between these data and mechanisms, and thereby to encourage power quality control through the phase balancing technique, which is applied near the loads where power quality problems arise. These phase balance mechanisms improve reduce induction motor harmonics and performance.**

Index Terms -- **Phase balancing, magnetic choke, power factor, system efficiency, power distribution, harmonics reduction, induction motor performance.**

I. INTRODUCTION

Contradictory reports have appeared in the recent literature concerning the properties and application of the AC magnetic phase balancing device, MPBD, which have discouraged the development of this useful technique of power quality control. This paper will analyze the methods and results of the several papers in order to clarify the perceptions and thereby encourage further research and application of this useful technique of power quality control.

In 1992, a magnetic, AC circuit was patented [1] which, when connected in parallel to an AC distribution system, in the manner of a power factor correction capacitor, increases the displacement power factor, reduces the amperage demand and the kilowatt demand, attenuates both amperage and voltage transients, and electrically compensates the effects of both current and voltage spikes and surges. This device is manufactured in modular size for 20 different voltages and phase arrangements and has been installed in industrial and residential distribution systems as a passive line conditioner. This capacitive device is most effective when installed parallel to a load of matched inductive impedance. For instance, when a MPBD is matched to a 100 HP, 480 volt motor, the MPBD reduces the demand by 20 amps and by between 3 and 10 kW. This 480-volt MPBD also corrects the power factor by 20 KVAR, reduces the 5th amperage harmonic by 47% and adsorbs and dissipates both amperage and voltage spikes and surges, thus protecting the motor load.

Discussing these initial results, the "True and False Device Report" [2] appeared in 1997. Also, in 1997, as a follow-up to the Canadian Standards Association (CSA) Certification, the CSA performed a test of a 600V MPBD [3]. In 1999, the Cutler-Hammer Engineering Systems Services, Inc. (CHESS) performed a test of a 480V MPBD installed at the Northrop Grumman Corp. [4]. The CHESS data were analysed and presented at the Power World 99 Conference [5]. Combining the data of [3,4 and 5], the latest understanding of the probable MPBD mechanisms will be discussed herein. We hope that this will encourage further research and application of this useful technique, which improves motor performance and corrects power quality problems close to the loads where they originate.

II. DISCUSSION

A. True and False Device Report

In 1997, "True and False Energy Saving Devices" [2], was presented at the IEEE/I&CPS Technical Conference, in Philadelphia. This report reviewed the state-of-the-art with particular reference to an unnamed but recognizable device. That device, herein designated as the MPBD, is described in references [1,3,4,5,7,8,9 and 10], and has been successfully installed as a passive line conditioner in a growing number of electrical distribution systems. This initial report [2] described the performance of the MPBD as "indeed mystifying" and, because the claimed results could not be reproduced in this author's lab [6], and the MPBD was identified as a "false energy saving device". No useful or reproducible data were presented therein.

B. Canadian Standards Association (CSA) Report

Also in 1997, results of a precise field study of the MPBD were released [3]. The CSA tested a MPBD installed on a panel powering five 600-volt induction HVAC motors. Redundant measurements were made at several points, and the report shows "an improvement in the voltage of +3.1, a reduction of 20.2 amps on the line, not load, an increase in power factor to 0.99, and kW was reduced by 4.1 on the line side". The CSA data are on file in the Eng. Dept of the CSA in Etobicoke, Ontario and were used to prepare Table 1.

From the data in Table 1 it is possible to construct phasor diagrams similar to Fig. 1, and to calculate by equation (1), the angle by which the MPBD amperage leads the source voltage, as well as, the instantaneous drop in the kW demand [7].

Table 1. Summary of CSA data where, e = volts, i = amps on line, PF = power factor and P = kilowatts.

	Test 1		Test 2		Test 3	
MPBD	**On**	**Off**	**On**	**Off**	**On**	**Off**
e	604	601	604	602	603	600
i	89	107	90	109	89	107
PF	0.99	0.86	0.99	0.85	0.99	0.86
P	92.1	95.6	93.1	96.4	91.9	95.5

The calculated results by (1) given in Table 2 show that the leading angle is more than 90 degrees, and that the calculated kW savings agree well with the measured kW savings. The leading phase angle of more than 90 degrees implies negative real power, however, this condition applies only to the amperage in the MPBD lead before it is fed into the motor circuit and cancelled by the system inductive reactive amperage.

A correcting average lead angle of 95 degrees is calculated from the CSA data. Capacitors can only correct the lead angle by less than 90 degrees. This calculation shows that the MPBD corrects the lead angle by a different mechanism. Also, the agreement between the measured and calculated kW data shows that the CSA data is indeed consistent.

Table 2. Measured and calculated kW reduction and calculated MPBD lead angle from the CSA data

	Δ kW meas.	**Δ kW calc.**	**Lead angle**
Test 1	3.5	3.6	94.7
Test 2	3.3	3.4	94.2
Test 3	3.6	3.6	94.7

Prior to the CSA study [3], John Reinsborough of Abitibi Price Inc. described the MPBD installed in their paper mills [8,9] and suggested that a portion of the demonstrated savings came from "the negative amperage which is achieved by the direction of the windings in the choke coils and reactors" and "the correctional voltage imbalance". Also, in 1995, Robert Emmet [10] described a multi-panel MPBD installation in a cold storage plant [10], in which the MPBD attracted transients and compensated for 20% voltage sag, thus averting major electrical damage and loss of product.

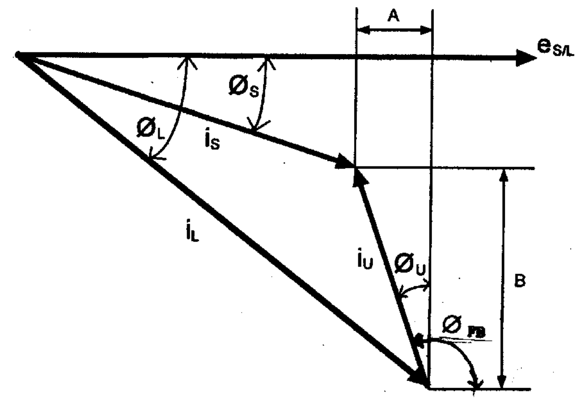


Figure 1. Phasor Diagram used to calculate the lead angle in Table 2. where,

i_S = Amperage Demand from Source
i_L = Amperage Demand by Load
i_U = Amperage supplied by MPBD

$e_{S/L}$ = Voltage of Source and Load
e_{S1} = Voltage with MPBD off
e_{S2} = Voltage with MPBD on

$A = i_L \cos \varnothing_L - i_S \cos \varnothing_S$
$B = i_L \sin \varnothing_L - i_S \sin \varnothing_S$

$\varnothing_U = \arctan(A/B)$, and $\varnothing_{FB} = \varnothing_U + 90$ where $\varnothing_{FB}$ is the angle by which the MPBD amperage leads the voltage.

The real power saving from the MPBD is calculated:

$$\Delta P_{calc} = \sqrt{3}\, e_{S1}\, i_L \cos \varnothing_L - \sqrt{3}\, e_{S2}\, i_S \cos \varnothing_S \quad (1)$$

C. Cutler-Hammer (CHESS) Report

In 1997, the Northrop Grumman Corp (NOC) installed an MPBD on a 150 HP, 480Volt chiller motor. NOC contracted with CHESS to measure the power parameters in this installation, and the resulting report [4] contains the most precise MPBD data to date. Based on these single-phase data, "A Magnetic Device for Improving Power Quality " [5] was presented to POWER SYSTEMS WORLD 99 in Chicago. From the precise, single-phase data, it was demonstrated that the MPBD, which magnetically Δ-connects the three electrical phases, improves the balance of the voltages and of the amperages between the three phases.

Because of the importance of the phase balancing effect, the data and discussion from [5], which first reported this effect, is summarized herein. Based on the single-phase amperage and voltage data from the CHESS Report [4], for each measurement condition, the average deviation from the mean of the three 1-phase amperages and voltages were calculated and are presented in Tables 3. The average deviations are uniformly smaller with the MPBD in the circuit, by 0.3 amps and by 0.2 volts, at the 75%, 90% and 100% load levels. This regular pattern of convergence demonstrates that the MPBD balances the amperage and voltage between the phases through the wrap-around magnetic chokes, Fig.3. These observed effects are small, however, in the CHESS Data, they are correlated with a 30% reduction of the total harmonic distortion of the amperage in the motor-MPBD circuit (see Table 4). During a transient spike, the imbalance of the phases would be greater nd the correction by the chokes would also be greater. The protection is greatest when needed most. When interpreting the data in Tables 3 and 4, please note that the motor was power factor corrected with a capacitor for 100% RLA amperage. The effects of the MPBD will be less at higher RLA because of that capacitor, which becomes redundant with the MPBD.

Table 3A. Analysis of 1-phase MPBD-Motor amperage data from CHESS Report [4]. RLA means Rated Load Amperage and Δi means the difference in amperage between MPBD ON minus MPBD OFF.

100% RLA	**MPBD ON**		**MPBD OFF**	
Phase	i	Δ i	i	Δ i
A	166.8	- 3.8	184.3	- 4.3
B	171.0	+0.4	189.6	+1.0
C	174.0	+3.4	191.9	+3.3
Averages	170.6	2.5	188.6	2.8
Δ MPBD	i = -18.0 amp		Δ i = -0.3 amp	
90% RLA				
A	139.3	-3.8	158.2	- 4.2
B	143.4	+0.3	163.4	+1.0
C	146.5	+3.4	165.7	+3.3
Averages	143.1	2.5	162.4	2.8
Δ MPBD	i = -19.3 amp		Δ i = -0.3 amp	
75% RLA				
A	111.7	-3.7	126.3	-4.9
B	115.5	+0.1	132.0	+0.8
C	118.9	+3.5	135.2	+4.0
Averages	115.4	2.4	131.2	3.2
Δ MPBD	i = -15.8 amp		Δ i = - 0.8 amp	

Table 3B. Analysis of 1-phase CHESS Voltage data

100% RLA	**MPBD ON**		**MPBD OFF**	
Phase	V	ΔV	V	Δ V
A-B	495.0	-0.3	495.2	- 0.4
B-C	496.2	+0.9	496.6	+1.0
A-C	494.7	-0.6	494.9	-0.7
Averages	495.3	0.6	495.6	0.7
Δ MPBD	V = -0.3 volt		Δ V = -0.1 volt	
90% RLA				
A-B	496.8	-0.3	495.4	- 0.4
B-C	498.0	+0.9	496.8	+1.0
A-C	496.7	-0.4	495.2	- 0.6
Averages	497.1	0.5	495.8	0.7
Δ MPBD	V = +1.4 volt		Δ V = -0.2 volt	
75% RLA				
A-B	495.6	- 0.5	496.5	-0.8
B-C	497.0	+0.9	498.6	+1.3
A-C	495.8	-0.3	496.8	-0.5
Averages	496.1	0.6	497.3	0.9
Δ MPBD	V = -1.2 volt		Δ V = -0.3 volt	

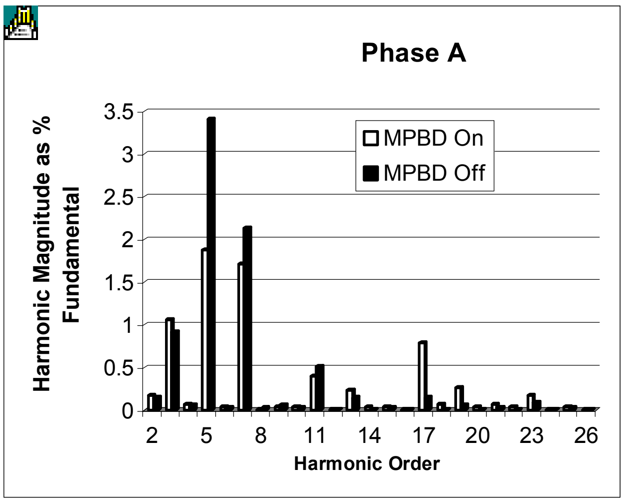
Table 4. CHESS Amperage Harmonic Spectrra with MPBD on/off for Phase A at 75% RLA Power Level.

Order	**on**	**off**	**Order**	**on**	**off**
2	0.165	0.142	14	0.043	0.000
3	1.055	0.918	15	0.033	0.028
4	0.066	0.057	16	0.000	0.000
5	1.879	3.414	17	0.791	0.142
6	0.033	0.018	18	0.066	0.000
7	1.714	2.134	19	0.264	0.957
8	0.000	0.028	20	0.033	0.000
9	0.033	0.057	21	0.066	0.028
10	0,033	0.028	22	0.033	0.000
11	0.396	0.512	23	0.165	0.085
12	0.000	0.000	24	0.000	0.000
13	0.231	0.142	25	0.033	0.026

The Cutler-Hammer 1-phase harmonics data are given in Table 4 for phase A at 75% RLA. Table 5 below shows that the MPBD has very small effect on the voltage harmonics. These typical values of each amperage harmonic magnitude, as a % of the fundamental, are shown in Fig. 2., which shows that the dominant, backward-rotating 5th harmonic stator field is decreased 50% by the MPBD. The slight increase in the odd harmonics, 17-23 does not affect motor performance because of their lower absolute magnitude and the slower field rotation.

Induction motor theory predicts that when the series-connected stator coils are nested together, that the opposed fields in the odd harmonics will add while those in the even harmonics will cancel. Theory also predicts that in three-phase systems, the opposing fields of the 3rd harmonic and the other triplen multiples will also cancel. These two effects reduce the even and trilpen harmonics as seen in the data of Fig. 2.

Fig. 2 Motor Harmonics for Phase A at 75 RLA with MPBD on/off.



All the raw data and the printed phasor and waveform graphs are in the CHESS Report [4]. A summary of these data calculated to 3-phases by the measurement instrument, is reproduced in Table 5.

Table 5. Summary of the data from the Cutler-Hammer Motor-MPBD Test by calculation.

Load	**100% RLA**		**75% RLA**		**50% RLA**	
PBD	ON	OFF	ON	OFF	ON	OFF
V	495.3	495.5	496.1	497.3	497.9	495.8
I	170.6	188.6	115.4	131.2	69.9	93.2
PF	0.998	0.996	0.997	0.968	0.915	0.826
kW	146.0	161.2	98.9	109.3	55.1	66.9
kVARs	-5.1	+8.1	+4.1	+16.3	+14.1	+25.4
kVA	84.5	93.5	57.2	55.3	34.8	46.2
V_{THD}	1.985	1.949	2.026	1.965	2.119	2.033
I_{THD}	1.938	2.844	2.884	4.206	3.990	4.911

Table 5 shows that in 3 phases: 1) the MPBD reduces amperage and power demand for an inductive-type load, 2) the MPBD improves the power factor of the load and 3) the MPBD decreases the total harmonic distortion of the amperage in the motor circuit by 30%.

D. Probable MPBD Physical Mechanisms

From the CSA [3] and CHESS [4] data, calculations suggest [5] certain physical mechanisms through which the MPBD affects power quality. To support the discussion of these mechanisms, a circuit diagram of the MPBD from one manufacturer is given in Fig. 3 which show 2 phase lines connected by a wrap-around magnetic choke wound on a highly permeable alloy core. In the 3-phase MPBD, the phase lines are symmetrically connected by 3 similar magnetic chokes. These magnetic chokes improve the phase balance, by producing amperage, through transformer action, which leads the applied voltage by more than 90 degrees, thus further reducing the source amperage. These magnetic chokes thereby increase the power factor, while the phase balancing attenuates the amperage and voltage transients. These combined effects through various mechanisms, increase the efficiency of the inductive circuit. The probable physical mechanisms through which these interactions occur are discussed below

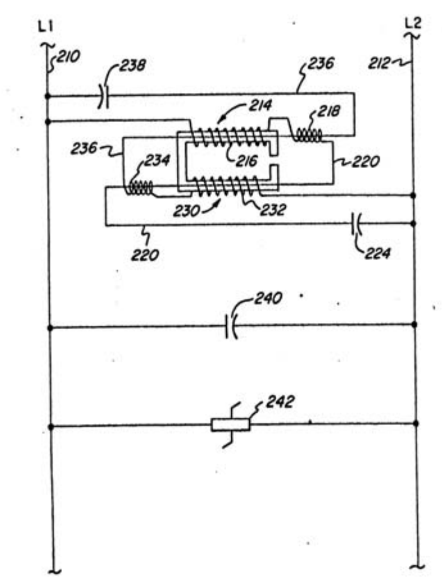


Figure 3. Wrap-Around Magnetic Choke

In Fig. 3, the two chokes, 214 and 230, in series with reactor coils 218 and 234, are wrapped around arms of the single core. This circuit is termed the wrap-around magnetic choke and is connected to the 2 phases lines through capacitors 238 and 224. Capacitor 240 and surge protector 242 further balance the circuit. In the 3-

phase MPBD three wrap-around magnetic chokes are Δ-connected symmetrically between the three phase lines.

i. *Displacement Power Factor Correction* The mechanism for power factor correction of the inductive circuit is the introduction of a resultant leading amperage generated by transformer action from the other phases. This amperage enters each phase from the other phases through the particular orientation of the windings in the chokes and reactors, as shown in Figure 3. Hassard [7] further described this mechanism from the CSA data and shows that the amperage from the MPBD leads the source voltage by 95 degrees, which cannot be achieved by capacitors.

In practice, a 3-phase MPBD at 480 volts corrects the power factor by injecting leading amperage of 27 amps into each phase. To maximize the i^2R savings and the load protection, it is best to locate MPBD close to the large inductive loads, but the location is not critical because the small capacitive leading amperage will eventually cancel inductive amperage somewhere within the system. The MPBD is superior to capacitors for power factor correction because the small, reactive amperage corrects by more than 90 degrees. The MPBD sizing and location are not critical, because the heavy circulating amperage and possible resonance between a capacitor and a motor are avoided. The MPBD does not radiate heat. Capacitors are not used on Navy Ships for power factor correction because the resonance between motors and capacitors leads to "migrating voltage hot-spots" and electrical damage [12].

ii. Adsorption of Transients. The balancing of the phase amperages and voltages, through the wrap-around magnetic choke, share transients between phases, and thus by, addition and subtraction, attenuate both the amperage and voltage transient spikes. The magnetic choke is a self-healing surge suppressor, which can operate indefinitely, as opposed to the sacrificial devices like MOVs that need replacement. The MPBD continually attenuates voltage and amperage transients, protecting the loads and increasing their useful lifetimes. To protect against large surges, which are not sufficiently attenuated by the chokes, MOV's within the MPBD provide transient suppression between each phase line and between each phase line and neutral. In several MPBD installations, the existence of the magnetic connection between the phases has attracted and dissipated large voltage and amperage spikes, which discharged through the MPBD, leaving the rest of the plant equipment undamaged [10]. The dissipated MOV devices within these MPBDs were repaired. Installing the MPBDs on panels throughout a plant near major inductive loads, isolates those panels from internal and external spikes and surges and through amperage reduction, maximizes the I^2R savings.

iii. *Compensation for Transients and Sags* The mechanism for the protection against short duration amperage and voltage transients and sags is the phase balancing in combination with the storage of energy within the RCL circuit of the MPBD. By distributing energy between the phases during voltage sags, the energy stored in the capacitor within the MPBD will keep the amperage and voltage steady for several cycles, the duration depending upon the load and the magnitude of the disturbance. Most sags and surges are of short duration and this compensation has proven to be the most valuable feature of the MPBD. During the short duration amperage and voltage sags and surges, the MPBD protects the circuit like a UPS.

iv. Control of Motor Harmonics The single-phase CHESS data [4] show that the dominant 5th stator harmonic is reduced by 47 % by the MPBD. Stator harmonics are produced by the complex field windings necessary to produce the rotating magnetic field. By balancing the phases, the MPBD reduces the unbalanced fields within the stator and thereby reduces the field harmonics and motor temperature. Reduction of motor harmonics improves motor efficiency by releasing energy for motor action and by reducing I^2R losses.

E. Increased* Circuit *Efficiency The mechanisms of the kW demand drop in the CSA and CHESS data are complicated to explain, because this effect is the sum of many small effects, which are difficult to quantify. The magnitude of kW reduction depends upon the particular phase imbalance and varies from case to case. The demonstrated phase balancing, and the 30% reduction of the amperage harmonic distortion [see Tables 3, 4 and 5], provides a starting point for the discussion of the probable mechanisms that increase circuit efficiency. The MPBD by equation (2) increases circuit efficiency by releasing useful power locked in phase imbalance and in amperage harmonics.

$$\Delta P_{MPBD} = 2[\, \Delta e\, \Delta i \Delta \cos\varnothing + \Delta P_{AHARM}] \qquad (2)$$

In (2), the first term is the power released within the motor when the inertia of mechanical rotation is better synchronized with the magnetic field rotation. The magnetic force vectors become more radially symmetrical with the spinning armature because of the phase balancing. The second term of (2) is the power released by the reduction of amperage harmonics and the factor of 2 in (2) indicates that the energy released by avoiding these conflicting forces and the consequent amperage harmonics is then available for motor action.

For complete discussions of the physical conditions within a polyphase inductive motor, see Langsdorf

[16], Alger [17] and Cochran [18]. It is beyond the scope of this paper to discuss the exact (im)balance of magnetic, electrical and mechanical force vectors. Suffice it to say that the phase balancing, PB, avoids asymmetrical, competing forces within the motor and releases the power for motor action. Table 6 lists the probable contributions of these various mechanisms and extends the estimate of the efficiency increase in the motor to include the transformer and the distribution system.

F. Discussion of Phase Balancing Mechanisms that Increase Circuit Efficiency

Identical windings between the phases within the MPBD will result in more closely balanced induced phase voltages. Given similar loading on each phase, the amperages will also tend to be more closely balanced. Of course, loading on each phase may not be equal, particularly if the MPBD is located on a panel rather than on a single motor, but the result will always be an improvement in the phase balance. Improved balance leads to smoother running 3-phase motors, with the rotating magnetic field in better synchronization with the mechanical rotation. This results in energy savings by reduction of motor vibration and noise and this conformity is the mechanism responsible for the 30% reduction in the motor circuit amperage harmonic distortion, $i_{THD.}$ These amperage harmonics are produced in the motor by conflicting mechanical and magnetic force vectors. Also, the unbalanced amperages and voltages in the motors give rise to eddy currents and increased i^2R power loss. As shown in Table 6, any efficiency increases achieved in the motor by phase balancing or by decrease in amperage harmonics should be multiplied by 2 because, by avoiding the retarding imbalance and the harmonics, the MPBD releases this energy for motor action.

The second term in (2) can be more completely quantified that can the first term. It is instructive to identify several saving mechanisms that are enabled when the MPBD reduces i_{THD} within the motor. In 1967, with the advent of variable speed drives, which produce voltage harmonics, Klingshirn and Jordan [13] investigated the "Polyphase Induction Motor Performance and Losses on Non-Sinusoidal Voltage Sources". Voltage harmonics induce time harmonics in the motor amperages and space harmonics in the magnetic fields. Removing with the MPBD the average time harmonics from the amperages is equivalent to avoiding the voltage harmonics and therefore this study is relevant to our problem. Furthermore, Langsdorf [16] discusses the losses of the transformer on pp 245-250. Both the ohmic loss and the hysteresis and eddy current losses are proportional to i^2R and these would all be reduced by the amperage reduction shown in Table 5. These transformer and distribution system efficiencies, as listed in Table 6, would be additional to the 10% KW reduction shown for the motor because the transformer was not included in the measured motor circuit [4].

Klingshirn and Jordan [13] identify the following motor losses that would be increased by harmonics. These mechanisms and equations for calculating the losses are included here to describe the several considerable motor losses that are reduced because the MPBD reduces the i_{THD} by 30%. The existence of harmonic amperages results in additional and sometimes rather large motor losses.

(1) Stator Winding Loss

The stator i^2R loss is given by the usual equation, with the additional term to account for the loss due to harmonic amperages.

$$\Delta P_{SW} = m r_1{}^3[(I_1{}^3)^2 + I_{har}{}^2] \qquad (3)$$

This loss may be considerably increased as a result of harmonics. Not only is it larger by the amount of the second term, but also the first term is increased due to the increase in magnetizing amperage already mentioned.

(2) Rotor Winding Loss

The rotor i^2R loss is given by,

$$\Delta P_{RW} = T n_{sl} / 7.04 \qquad (4)$$

For a constant torque load, this loss is increased by a negligibly small amount with non-sinusoidal excitation. The increase is due to the increase in slip speed to overcome the small negative torque produced by the harmonic amperages.

(3) Core Loss

The stator core loss is a function of the flux density in the stator core. It is larger with harmonics due to the higher peak flux density previously discussed in conjunction with the magnetizing amperage, but can be neglected in the total loss evaluation.

(4) Friction and Windage Loss

Loss is not influenced by harmonics.

(5) Rotor Harmonic Loss

Rotor harmonic loss can be the largest loss attributable to the harmonic amperages. It is appreciably increased by the rotor deep-bar effect, which is a large effect at the harmonic frequencies. Because of this variation in rotor resistance, the loss due to each harmonic current must be considered separately. For the k^{th} harmonic, the loss is,

$$\Delta P_{RH} = m(I_k^r)^2 r_k^r \qquad (5)$$

The summation of these losses for all the harmonic frequencies gives the total rotor loss.

(6) Stray Load Losses

Alger, Angst and Davies [14] have thoroughly treated these losses and included equations for calculating them. These equations have been applied to the motor with harmonic amperages, and they indicate a large increase in some losses. These individual losses with equations are discussed below.

(7) Rotor Zig-Zag Loss

This loss is due to pulsating flux in the rotor teeth due to slot permeances and slot MMF harmonics. This flux induces amperages in the rotor bars, with a resulting i^2R loss. The analysis by Alger et al. leads to,

$$\Delta P_{RZZ} = mC_{db}r_1^r[C_0I_0^2 = C_LI^2] \qquad (6)$$

The authors give curves to find the machine constants C_o and C_L. The parameter C_{db} is a constant to account for the deep-bar effect at the slot harmonic frequency. With the time harmonics present in the stator amperage, I_o is taken to be the fundamental no-load current and I is the entire stator amperage including harmonics. Because both Io and I are substantially larger with harmonics, this loss can be several times larger.

(8) Stator End Loss

Another loss described by Alger et al. is the eddy current loss in the stator end laminations due to leakage flux entering these laminations axially. The equation given with some changes in notation is,

$$\Delta P_{SE} = 0.3C_1m(I_1^3)^2f \qquad (7)$$

where C is a machine constant and 0.3 is a power factor applied to the leakage flux. To apply this equation to the motor with time harmonics in its stator amperage, it is necessary to consider the fundamental and each harmonic.

(9) Rotor End Loss

An end loss like that described above for the stator also occurred in the rotor end laminations. Each harmonic will create a loss, which is taken to be equal to the stator end loss for that harmonic. The sum of all these harmonic losses must also be calculated.

(10) Crawling Loss or Loss of Motor Torque

In their comprehensive "Handbook on Electric Motors", Engelmann and Middendorf [15] describe motor crawl, which results in loss of motor torque close to the harmonic synchronous frequency. Langsdorf [16] also described motor crawl as being a property of inductive motors long before the VFD and other solid-state devices introduced severe harmonics. Motor crawl is caused by perturbation of the torque-speed curve as the motor accelerates through the harmonic synchronous speeds while starting. The stator windings, required to give the rotating fundamental magnetic field, generate strong 5th and 7th order amperage harmonic fields, which are reduced by the MPBD. The harmonic fields rotate at slower synchronous speeds, 1/n of the fundamental field speed. At motor speeds above the synchronous speed, the forward rotating harmonic fields, 7, 13, and 19, exert a retarding force, as is the case for the backward rotating fields, 5, 11, 17 and 23, at all speeds. Therefore, over the last 80 years considerable effort has been devoted to reduce these harmonic stator fields by adjustments in the internal motor design. Now, by connecting in parallel the MPBD, it is possible to obtain improved starting characteristics and greater motor efficiency at all speeds. The systematic study of motor harmonic fields was developed by Alger [17] and reviewed in quantitative detail by Cochran [18].

These 8 significant losses in motor efficiency due to the presence of amperage harmonics (Term 2 in Equation 2) have been described in detail to show 8 probable mechanisms by which the 30% reduction of the total amperage harmonic distortion results in increased motor efficiency. Klingshirn and Jordan obtain good agreement between the harmonic losses calculated by equations (3,4,5,6 and 7) and the measured losses of motors running at no-load and full-load. Consult their paper for details and symbol definitions.

From the losses described in equations (3, 4, 5, 6, and 7), equation 2 can be rewritten:

$$\Delta P_{MPBD} = 2[\ \Delta e \Delta i \Delta \cos\varnothing + \Delta P_{SW} + \Delta P_{RW} + \Delta P_{RM} + \Delta P_{RZZ} + \Delta P_{SE}\ ] + i^2R_{TRANS} + i^2R_{DISTR} \qquad (8)$$

Equation (8) is the basis for estimating the values in Table 6. The values of efficiency increase in 6A are given by the first term of (8) and are chosen to approximate the measured 10% from the CHESS Report [4]. The next five terms in (8) are estimated to be 3% and the third term to be 2%. These last two estimated values appear to be large, until compared with the reduction of i of 10% to 30% and the reduction in i_{THD} of 30% as shown in Tables 3, 4 and 6. The last two terms give the i^2R savings in the transformer and in the rest of distribution system, which brings the total to 15%.

Table 6A, below, considers the effect of the MPBD on the motor and Table 6B considers this effect on the transformer and the distribution system. It should be realized that through phase balance, the retarding, imbalanced motor forces and the retarding amperage harmonics are reduced. The MPBD therefore releases this same energy for motor action that would otherwise be trapped in the harmonics and unbalanced forces. The increase in the motor efficiency by these 8 mechanisms is estimated to be 8%, which when added to the i^2R loss reduction of 2% in Table 6A adds up to the 10% increase in efficiency measured in the Cutler-Hammer Motor-MPBD Test [4]. Remember that the efficiency increase is proportional to the phase imbalance and is found to be higher in older plants where there are more single-phase loads on the three phase motor circuits. Also, the presence of single phase loads, near three-phase motors, such as defrost circuits, can contribute to motor circuit phase imbalance.

The increased efficiencies of the transformer and the distribution system would be additional to the measured 10% increased motor efficiency. The motor effects are detailed in Table 6A, while the effects of the MPBD on the rest of the distribution system are estimated in 6B. As noted above, the efficiency increase of the transformer is due to the pronounced i^2R and harmonic savings and its lower operating temperature. These savings in the transformer are estimated to be 3%, and the i^2R and harmonic savings in the rest of the distribution system are estimated to be 2%. Therefore, the savings in the motor, transformer and distribution system, not including the generator, total to 15%.

Now finally, the system savings are realized as a 15% fuel saving at the generator, which is required to generate 15% less power. The system savings can also be expressed as a release of 15% of the system capacity. For these estimates to be valid, all loads would be induction motors balanced by MPBDs. We recommend further system testing with the MPBD to verify these estimates.

Table 6. Probable Phase Balance Mechanisms that Increase Total Circuit Efficiency

Mechanism	**% Increase**
A. Motor Circuit (measured)	
1. i^2R reduction, effect on motor	2
2. PB of e, removal retarding force	1
3. PB of i, removal retarding force	1
4. PB of e, release of retarding energy	1
5. PB of i, release of retarding energy	1
6. PB of i, reduction of harmonics	2
7. PB of i, release of harm. energy	2
Total Efficiency Increase for A =	**10%**
B. Transformer-Distribution Circuit (estimated)	
1. i^2R reduction, effect on transformer	3
2. i^2R reduction, effect on Distribn. Sys.	2
Total Efficiency Increase for B =	**5%**
C. Generator Fuel Saved: 15% less power	15
Total Fuel Saving at Generator =	**15%**
D. Released System Capacity =	15
Total System Capacity Released	**15%**

CONCLUSIONS

Unlike any other device, the MPBD both corrects the power factor and mitigates spikes and surges to protect the loads. Also, by balancing the phases, the MPBD reduces the harmonic amperages of induction motors and increases their efficiency and useful lifetime. If the generator and transformer had been included in the CHESS motor test circuit, then it is estimated that the results would show that the total electrical system would do the same amount of work using 15% less energy. Due to the high quality of the CSA and the CHESS data, the probable mechanisms of the MPBD have been suggested. Because of the fundamentally different and highly beneficial nature of magnetic phase balancing in poly-phase circuits, it is hoped that this discussion of the MPBD mechanisms, upon reflection, will increase the interest in research and application of this important method of power quality control, which is applied close to the loads where the PQ problems originate.

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