

Controlling Unbalanced Supply in Weak Utility Systems

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Building new industrial plants in developing rural counties, as shown in Fig. 1, has the advantage of low land cost, honest labor and lower taxes; however, the ability of the utility grid to supply power must be carefully planned in advance of construction. When a new plant comes on line, rural neighbors often suffer degraded power quality and all must adapt protective measures in order to maintain the electrical peace. In these weak or new utility supplies, the case of unbalanced phases presents a difficult challenge, particularly to 3-phase motors, because the sources of imbalance arise from numerous unsymmetrical conditions. Unsymmetrical transformer windings or transmission line impedance, unbalanced 3-phase loads or a large single-phase load cause unbalanced supply. Usually phases are only balanced at the generator, and sources of imbalance can be found throughout the system. However, regardless of the cause, in an ac-connected machine, even a small voltage imbalance can induce large negative sequence currents and harmonics, due to the relatively low negative sequence impedance of a motor. Induction motors are particularly sensitive to imbalanced operation, since harmonics in the stator cause local heating, which seriously affects the life of the machine.

Conventional remedies for phase imbalance begin with equal distribution of the single-phase loads. This can extend to involve costly modification of the incoming substation equipment, redesign of the feeder-line input to the various loads, or perhaps retrofit with an oversized machine. In 1985 the use of back-to-back thyristors or VCRs has been suggested to balance phase voltages [1].

As shown in Fig. 2, these thyristor pairs in series in each phase provide unsymmetrical variable supply impedances, which can be used to continually balance the voltage across the motor phases [2]. This same configuration has also been used more recently to control voltage flicker resulting from voltage drawdown associated with motor starting [3]. Thyristor switched capacitors were used to control series capacitors to achieve the desired voltage control in a weak utility supply that did not provide sufficiently high short circuit current to adsorb the resulting harmonics.

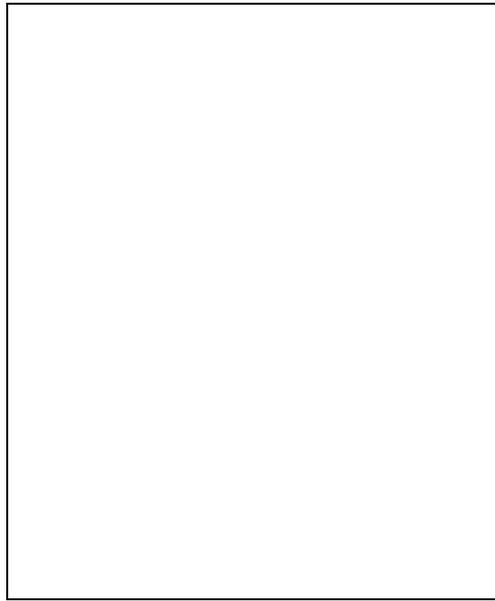


Fig.1. Bookmobile in Bayou de Large, 15 miles south of La Houma, Louisiana. Bringing change to rural areas can often upset the boat.

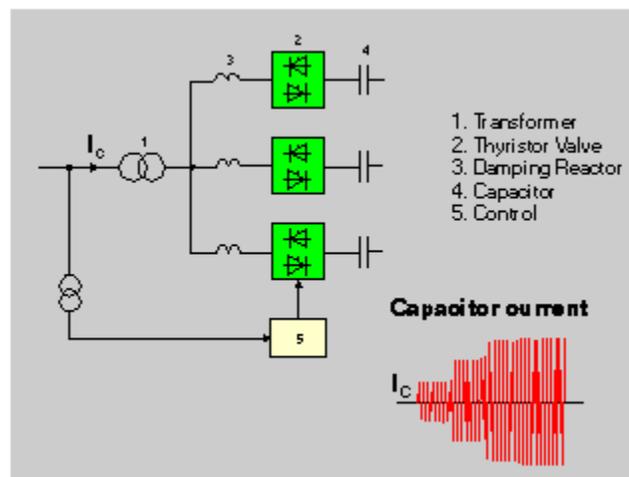


Fig. 2. Thyristor switched series capacitors used to balance motor phase [1, 2] and to control voltage flicker [3].

In the case of the thyristor-switched-series-capacitor (TSSC) unit used to control the voltage flicker in a rural county [3], after installation, thyristor failures caused numerous TSSC unit trips. The cause was traced to poor temperature control. Dirty filters, clogged airways and insufficient cooling capacity have all contributed to numerous component failures. Also, series thyristors contribute severe harmonics to the system and their control system is impacted by the same harmonics. Harmonic filters are usually employed to increase thyristor reliability. Voltage harmonic distortion can often

be controlled by a single high pass filter, but the reduction of current harmonics usually requires installation of multiple tuned filters, each of which reduces only one of the many harmonic frequencies produced by the solid state power electronics. Thus, filters to bring equipment into compliance with IEEE 519-1992 tend to be large, complex and costly. Our experience is to avoid power electronics and to use alternative means to balance phases and support voltage.

In weak utility systems because of more direct contact between neighbors, it is not advisable to use unreliable equipment that produces heat or harmonics. The release of IEEE Std. 519-1992, "Recommended Practices for Harmonic Control in Electric Power Systems", leads to new concerns and restrictions by utilities about the harmonic effects of thyristor controller equipment. Although IEEE 519-1992 addresses only voltage distortion, the latest version severely limits the amount of current distortion allowed. Harmonics are more severely restricted in weaker supply systems with lower short circuit currents. IEEE 519 discourages the use of thyristor controls in these systems. Also, the option of upgrading to an oversized machine would waste precious amperage capacity. In weak utility systems, we recommend the phase balancing USES Unit, which is multi-purpose equipment with many additional beneficial effects. The following paragraphs describe the characteristics of these low maintenance passive line conditioners.

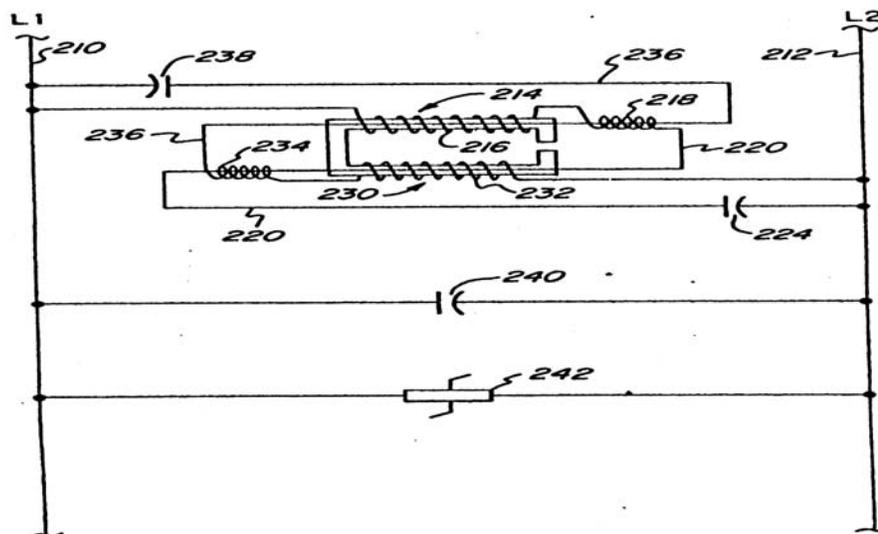


Fig. 3. Three wrap-around magnetic chokes connect the phase lines in a delta, 3-phase USES Unit. This robust circuit uses 6-10 AWG wire, resists lightning surge and does not heat up.

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USES TEST PROGRAM

In 1998 at the Northrop Grumman Corp. (NGC) Test lab in Sykesville, MD, a 3-phase, delta USES Unit", was installed parallel to a 150 HP chiller motor in the HVAC System [4, 5]. To evaluate claims that the device improved power factor (PF) and reduced real power (kW) demand, a test program was designed to precisely describe the effect on the motor circuit. Cutler-Hammer Engineering Systems Services, Inc. (CHESS) [6] performed the test under separate contract and the results have been published and discussed [7, 8, 9,10]. As continuing discussion of the data, herein, we suggest how, by balancing the 3-phase currents and voltages, several parameters of Power Quality are remarkably improved. Power Quality is described as the best quality power to operate specific equipment or process with the lowest level of operating problems. CHESS data are shown in Tables 1 and 2 and in Figs. 4 and 5.

USES SURGE SUPPRESSION

Between October 1993 and July 1994 Icelandic USA, Inc. of Cambridge, MD installed eleven 480-volt, 3-phase USES Units parallel to the main compressor motors in the north end of that plant [11]. On Saturday, November 26, 1994, major electrical damage occurred in the south end of the plant. Sifting through the evidence and from the utility records, they believe there was a 20% voltage sag on 3-phases for about 10 cycles. In the plant south-end, the sag knocked out one of the 1-phase transformers that serve the light weekend loads. The phase protection in the south-end never tripped, and its magnetic coil melted. Several motors were damaged by single-phase current, motor starters failed and contacts were welded together. No damage occurred in the north-end even though all twelve (12) 1-phase transformers on the roof were wired in parallel. The installed 11 USES Units protected all the north-end motors and their associated protective equipment, which drew 90% of the current during the weekend. These units not only saved the large motors from damage, preventing a loss of temperature in the freezers, but they protected the step-up transformers. The investment in USES Units was repaid by this single incident. Icelandic went on to install 55 USES Units.

In October 2001, according to utility records, 1000-volt spikes hit Icelandic in two or three phases. The spikes had been caused by a fault from a circuit breaker test circuit in a neighboring plant. At Icelandic, the hit was adsorbed by two USES Units, which were the only damage in the plant. The units were analyzed and the thermal damage was repaired at USES Manufacturing, Inc. In both units, the plastic insulation was burned and the vapor pressure was sufficiently elevated to separate the lid from the polymeric unit enclosure. The first unit remained on-line until the internal terminal block fused and evidently absorbed sufficient transient energy to protect the rest of the plant. The second unit also heated up but remained on-line throughout the event. Both units were repaired and reinstalled. Because of the magnetic connection between the phases, during these extreme conditions, the units sacrificially attracted and dissipated the transients without other damage or loss of product. There were 12 million pounds of fish in storage. Two similar surge suppression events have been recorded at the IUSA Copper Wire Plant in Pasteje, Mexico.

USES POWER FACTOR CORRECTION

In 1985, the plant PF at Icelandic USA was determined to be 0.85. About 20 capacitors had been added in parallel to the motors and the initial interest in USES in 1993 was for power factor correction. By 1999, as the 55 USES units were connected to the plant circuit, the PF rose from 0.89 to 0.99. The added USES Units were compatible with the existing capacitors. For example, when testing multiple USES Units on the Motor Control Center (MCC) of a 500 HP 480 volt motor, 4 units brought the PF up to 0.98, 5 units to 1.00 and 6 units to 0.98 on the capacitive side. As a result of the findings of the above test, Icelandic installed 4 units on that MCC as shown in Fig. 4. Each 480-volt USES Unit produces about 10 KVARs of PF Correction.

USES Units have several benefits over capacitors (Caps) for PF Correction:

1) LOCATION NOT CRITICAL. With USES, the location of the Units is not critical because a small, capacitive current linked from an adjacent phase makes the correction. With Caps, location, sizing and switching the Caps with the loads is important because of the large circulating currents. One 480 volt, 3-phase delta USES Unit balances a 100 HP Motor

2) BREAKERS, NOT FUSES. With USES, 3-pole magnetic breakers are used to disconnect 3 phases at once to keep the circuit balanced. With Caps, non-reusable fuses are necessary to prevent thermal tripping.

3) RESONANCE. With USES there is no possibility of destructive resonance because of the damping effect of the phase balancing. With Caps, voltage variation is caused by unstable resonances, which form in the tank circuits with the motors. Harmonics in the tank circuits can reinforce the resonant frequency and damage connected loads. Caps have lower impedance at the higher harmonic frequencies thus allowing larger currents to blow the Cap fuses. Because of the possibility of resonance leading to "voltage hotspots", PF CAPS are not used on Navy ships [13].

4) LOW MAINTENANCE. USES and Caps should both be accessible for the inspection of the contactors. With USES there are indicator lights on each phase. Caps should be frequently checked with a clamp-on ammeter to be sure they are operating.

5) MOTOR DAMAGE. Over compensation with Caps can lead to the circulating currents exceeding the magnetizing current of the motors, resulting in self-excitation. With USES, because of the low, correcting currents, there is no possibility of self-excitation or resonance.

6) STABLE VOLTAGE. Leaving Caps connected during lightly loaded conditions leads to over-voltage, which can damage connected loads. With USES connected, the voltage

is balanced between the 3 phases, constant voltage is maintained and voltage transients are attenuated.

7) MORE EFFECTIVE APPLICATION. Because of the danger of over-compensation, when using Caps, the PF has traditionally been corrected to 0.90. With USES Units, small capacitive currents cancel the inductive currents, and if there is over-correction, then only a small, stray current is involved. Therefore, with USES Units, the PF can be corrected to 1.00. This higher plant PF reduces the utility bill further, because above 0.90, the PF Penalty becomes a PF credit. If there is no PF Penalty, then the greater system impedance balance near 1.00 PF minimizes the current throughout the system and therefore the I^2R power loss.

8) MORE EFFECTIVE LOCATION. Because of the large, surging currents, Caps are usually located in banks near the service entrance, where the conductors are large. These cap banks affect the plant PF for billing purposes only. Because the locations of the USES Units are not as critical, they can be placed close to inductive loads and therefore they reduce the amperage demand throughout the plant for greater benefits and savings. Also, a USES Unit on each panel isolates that panel from transients and surges of amps and volts.

9) MULTI-PURPOSE EQUIPMENT. Caps heat up and use power. USES Units are magnetic connections between phases. They do not heat up and they save power. Furthermore, USES Units provide several additional benefits as will be discussed below.

USES PHASE BALANCE

A USES Unit provides a balancing magnetic connection between phases. The magnetic chokes store and release system capacity, thus stabilizing voltage. The cores of the chokes are split and will not resonate or saturate. In the process of balancing phases, a small reactive current in each USES lead (4 to 30 amps) corrects the PF. By magnetically connecting the phases close to the load, USES balances the phases thus relieving electrical stresses, increasing the efficiency and reduces the harmonics of three phase motors. The transformers likewise have less hysteresis and eddy current loss, less harmonic loss and increased efficiency [15, 16].

USES TRANSIENT ATTENUATION

At Icelandic USA, Inc. USES maintained 3-phase voltage or amperage sags and surges by contributing its capacitive energy through the chokes to the 3-phases of the branch circuit. USES also attenuated 1-phase transients of voltage or amperage by sharing amplitude between the phases. A spike is suppressed to a manageable level and adsorbed into the system. The magnetic chokes in USES are self-healing, inductive suppressers and handle most of the circuit imbalance by energy distribution between the phases over time. USES units do not heat up, and there is no thermal cycling of the parts, therefore, they give long service. To protect the USES Units and the branch circuits from large transients associated with ground faults and lightning, a Metal Oxide Varistor (MOV) is included in each phase of the USES Circuit. The MOV's

dissipate the heat after each surge. Each MOV is in series with a lamp, which occasionally indicates the need for MOV replacement. If a USES Unit is connected to only 2 phases, it will try to balance the third phase and the 2 lights will be dim. Checking the phase contactor on the dark phase can usually restore unit balance.

USES HARMONICS REDUCTION

The most useful data, shown in Table 1, is from the CHESSE on/off test of a 150 HP Chiller Motor [6]. Table 1 show that in the motor circuit a 30% reduction in amperage harmonics coincides with the 10% reduction in kW demand. The 1-phases voltage and amperage show better balance with USES on which indicates that phase balancing and reduced current harmonics is the basic mechanism of USES. With the reduced and balanced eddy currents, the motor runs cooler and the energy that was trapped in amperage harmonics would be released for motor action. Thus USES also improves the harmonic power factor of the motor and of the plant, which yields cooler, more reliable distribution system.

Pwr. Var.	100% RLA		90% RLA		75% RLA		50% RLA	
	ON	OFF	ON	OFF	ON	OFF	ON	OFF
V_{LL}	495.3	495.5	497.2	495.8	496.1	497.3	497.9	495.8
Abs. Chg.	-0.2		1.4		-1.2		2.1	
I_L	170.6	188.6	143.1	162.4	115.4	131.2	89.9	93.2
% Chg.	-9.50%		-11.90%		-12.10%		-25.00%	
PF	0.998	0.996	1.000	0.991	0.997	0.968	0.915	0.836
% Chg.	0.20%		0.90%		2.90%		7.90%	
KW	84.3	93.1	71.1	79.8	57.1	63.1	31.8	38.6
% Chg.	-9.50%		-10.90%		-9.50%		-17.60%	
kVARs	-5.1	8.1	0.6	10.9	4.1	16.3	14.1	25.4
% Chg.	-163.00%		-94.90%		-74.80%		-44.50%	
KVA	84.5	93.5	71.0	80.5	57.20%	65.2	34.8	46.2
% Chg.	-9.80%		-11.80%		-12.30%		-24.70%	
V_{THD}	1.985	1.949	2.084	1.932	2.026	1.965	2.119	2.033
% Chg.	0.80%		7.90%		3.10%		4.20%	
I_{THD}	1.938	2.844	2.372	3.31	2.884	4.206	3.99	4.911
% Chg.	-31.90%		-28.30%		-31.40%		-18.80%	

Table 1. Summary of 3-phase data from CHESSE on-off Test. The Values were calculated from single-phase measurements. Single-phase data can be found in CHESSE Report [6].



Figure 4. Bank of 4 USES Units connected to the H-10 Motor Control Center for 500 HP Compressor H-10 at Icelandic USA, Inc. Individual units are wired to individual 30 amp breakers and the connection passes through a 150 amp master breaker to the incoming power lugs in the MCC via the cable at lower right.

CONTINUOUS PLANT OPERATION WITH USES

Perhaps the most valuable contribution to the overall plant operation efficiency is fewer production interruptions for maintenance. Modern plants are complex, highly coordinated operations with the greatest cost being labor. Labor costs continue during down time when overall production becomes negative. By balancing and protecting the electrical system, USES keeps the plant operating smoothly and the profits high.

USES CIRCUIT EFFICIENCY INCREASE

With balanced phases the amperage harmonics are reduced in operating motors. The Cutler-Hammer test showed that when the phases are balanced by USES, this energy is released for motor action and the kW demand of the 150 HP motor is reduced from 93 to 84 kW. The amperage is also reduced by 20 Amps by the improved power factor. The entire distribution system is cooler and capacity is released, also, several losses are reduced in the transformer, which is essentially a motor at zero rotation. The improved efficiency of any circuit by USES is proportional to the degree of phase imbalance correction. Until this was understood, the varying results of single load tests evaluated. Phase imbalance is often transient. USES is your electrical watchdog, which balances the phases constantly and is in service when you need it.

In 1997, Parsons [17] reported, "Power Conditioner dramatically slashes manufacturers electric bills". These conditioners installed by Strathmore Electric of Stamford, CT were USES Phase Balancing Units. In addition to protecting and cooling the circuit, USES continually saves at the meter. From these savings alone and independent from the other protective features, a typical USES payback is 2 to 3 years. To receive maximum payback and protective benefit, USES Units should be distributed throughout a plant, on each panel with a significant inductive load. A 4-wire WYE USES Unit is typically placed at the service entrance to attenuate external transients on the phases and the neutral. A distribution system fully engineered with USES Units is balanced for greater efficiency and protected against externally and internally generated transients. Each panel within the plant is isolated with USES for effective damage control.

NEW USES HARMONICS DATA

Spectral harmonic data from the CHESS Test [6] is shown in Table 2. The typical data are shown here for the A Phase at 75% RLA. Table 2 and Fig. 5 show that the USES Unit decreases the dominant 5th harmonic of the stator field by 46%. There is a slight increase in the higher harmonics, 17th-23rd, however, their effect on motor performance may be neglected because of the much smaller absolute magnitude of these field vectors and the much slower harmonic field rotation. Also, the magnetic reactance projected across the air gap by the stator phase belt harmonic fields decreases with the

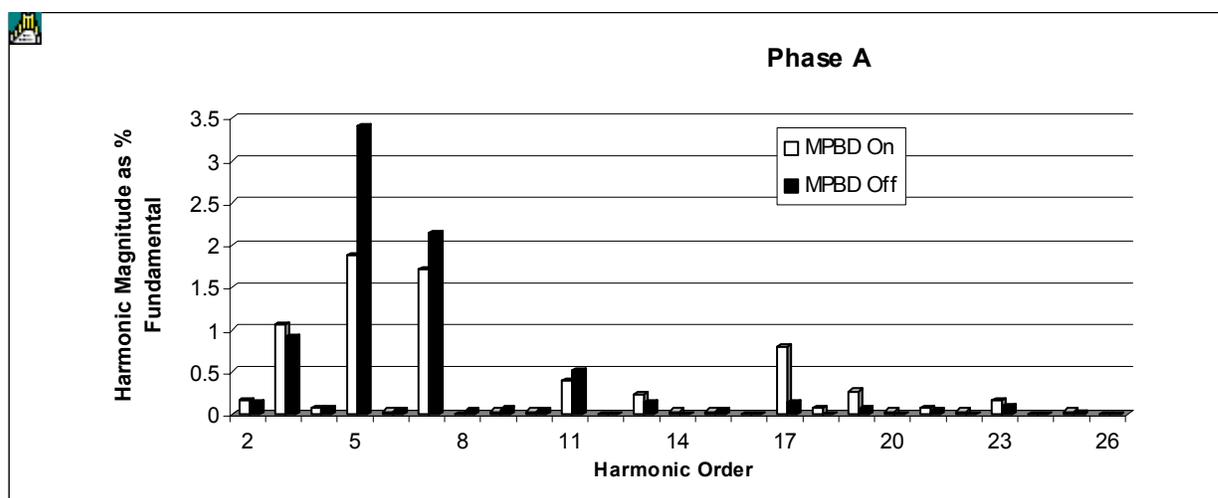
4th power of the harmonic order and therefore the effect of the 17th-23rd fields on motor operation is very small.

Table 2

Cutler-Hammer Motor Harmonics Data for 75 RLA

Harm. Order	ON	OFF	Harm. Order	ON	OFF
2	0.165	0.142	14	0.043	0.000
3	1.055	0.918	15	0.033	0.000
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	0.057
8	0.000	0.028	20	0.033	0.000
9	0.033	0.057	21	0.066	0.028
10	0.033	0.026	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

Fig. 5 Motor Harmonics for Phase A at 75 RLA with USES on/off. MPBD = Magnetic Phase Balancing Device



These new harmonic data show that by balancing the phases, the wrap-around magnetic chokes with USES, eliminates by half the backward rotating 5th order stator

harmonic field, reduces by 20% the 7th harmonic and shifts some of this harmonic energy above the 15th order, which do not effect motor performance. This consequence of phase balancing provides major opportunities for advances of induction motor design and motor efficiency, which were not possible in the hay-day of motor research, because there was no means of balancing phases by a single circuit component. This 50% reduction of the 5th harmonic in induction motor circuits is responsible for most of the 10 % increase of motor efficiency shown in [7, 8, 9, 10] and this is an important property of the USES Unit. This new capacity to significantly reduce the backward rotating 5th harmonic without modifying the coil pitch and coil distribution factors, K_p and K_d , This feature of USES will motor and circuit design to be reviewed and optimized. The installation of the USES Unit in the existing power distribution circuits parallel to the motors, particularly in weak utility systems should provide major additional benefits, such as phase balancing, power factor correction, transient protection and surge absorption, in addition to increasing motor efficiency and performance characteristics by controlling the 5th harmonic of the stator field. Phase Balancing is the wave of the Future.

SUMMARY

Using solid-state power components like Thyristors and SCRs to balance electrical phases produce voltage and current harmonics, which must be controlled in weak utility systems. The magnetic USES Phase Balance System decreases harmonics and has other beneficial effects. New harmonic data from a USES-Motor test circuit shows that USES decreases the 5th and 7th harmonic, which improves motor performance. USES also attenuates voltage and amperage transients, carries the distribution system through short sags and surges, increases the efficiency and lowers temperature of induction motors and increases both the displacement and harmonic power factors. USES is installed in parallel, does not cycle thermally, requires little maintenance and has long service life.

We would appreciate your questions.

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