Energy Saving Analysis of Harmonic Suppression in a Distribution Network

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Abstract—**Harmonic in power systems would not only reduce the work efficiency of a distribution network and electrical equipments so as to cause faults, shorten service life of the network, but also increase the system loss, reduce the power factor and efficiency of electric consumption utilization, and cause greater economic loss. In this paper, through the analysis of generation mechanism of harmonic in power systems, and the effect of harmonic on a variety of electrical components, found that harmonic suppression has a certain energy-saving efficiency theoretically; finally, verified through an example when cost used for harmonic suppression is lower than electric fee saved, eliminating harmonics would improve the power quality, and at the same time obtain certain economic benefits.**

Keywords—Distribution Network; Harmonic; Energy Saving; Economic Benefits

I. INTRODUCTION

Ideally, the power supply should always provide the perfect sinusoidal voltage for each user. However, due to some reasons, it is often difficult to maintain this ideal state for the power supply companies, there is always bias between the actual current and voltage waveform and the standard sine wave, namely waveform distortion. We transfer this kind of waveform distortion into harmonic distortion [1][2].

Harmonics are mainly from three aspects: one is the harmonic power of low quality; second is the harmonic from the power transmission and distribution system; the third is the harmonic generated by electrical equipment. In the modern power system, power electric equipments are used more and more widely, loads of nonlinear, impact, volatility and asymmetric substantially increase, make power quality pollution such as voltage wave, voltage sag and harmonic become more and more serious, the power quality problems brought influence to life and production, which have been concerned by the power supply enterprises, users and power equipment manufacturers and other electric customers, and harmonic is one of important aspects.

Nonlinear loads in a power system is the root of harmonic generation, and can be divided into three categories including iron magnetic saturation type (various core equipments), electronic switch type (various kinds of electrical and electronic equipments) and arc type (AC arc furnace and AC welding machine). With the development of power electronic technology, scale of the network is larger and larger, the harmonic pollution in the system is also more and more serious, and especially that harmonic pollution in the low voltage distribution network is much more obvious. Influences

of harmonics on distribution network are manifested in the following aspects [3][4][5][6]:

a. The effect on power equipments

Influence of harmonic on parallel capacitor group is the most significant. According to statistics, there are about 70% harmonic faults occurring in capacitor group. Research indicates that, the capacitor insulating in mineral oil can maintain two years under 5% of total distortion voltage, and dielectric loss coefficient approximately doubled. With the help of the harmonic, damaged power cables also increased significantly. The former Soviet Union once compared the two cables laid in the similar ambient temperature at the same time, one of them operated at the basic sinusoidal voltage, and total harmonic distortion voltage of the other one is 6% ~ 8.5%. After 2.5 years of operation, the leakage current of the latter increased an average of 36%, more 43% than the former after 3.5 years of operation.

b. Resonance

The capacitors with power factor compensation are widely used in power system, at the same time, there is distributed capacitance in equipments and lines, which are combined with the emotional component of the system (for example, line, reactance of transformer), at a certain frequency, the resonant conditions may exist in series or in parallel for such combination. When harmonic in the system is large enough, dangerous over-voltage or over-current of harmonic would be caused. Usually the harmonic source is regarded as a constant current source. Harmonic resonance is most commonly found in the bus with harmonic source, because there is not only harmonic source but also Shunt Capacitors / Cable / power supply transformers and motors in the bus, and these devices are often changing, easy to form the resonant condition.

c. Effect on electrical equipments

(a) Television. When more harmonic in voltage waveform, image distortion would occur on TV, and the picture and brightness would change, even make TV images "rolling".

(b) Lamp. Fluorescent lamps with ballast and mercury lamps, in order to improve the power factor, often install a capacitor, the combination of lamps and ballast and power supply circuit has a natural oscillation frequency. For example, a harmonic frequency was similar with this, resonant will be caused, and even damaged; the ordinary incandescent lamp will be flashing when harmonic at the frequency of 5 ~ 20Hz,

which would cause people visual discomfort (called "flicker")[7][8].

(c)   The computer. The content of harmonic voltage in the power supply of computer is too large, which cause calculation error or program out of line. Therefore some manufacturers provided an acceptable limit of harmonic voltage for computer and data processing system.

(d) Converter. Converter itself is harmonic source, in addition to characteristic harmonics and little non characteristic harmonics according to the rectifier pulse number, short circuit of AC power network for short time (several Microseconds) in the process of rectification, will cause depression wave distortion of voltage waveform (commutation notch). Depression wave distortion may affect synchronization of the communication device or normal operation of other devices controlled at zero voltage[9][10].

(e) Overload passing low-voltage neutral line. when three-phase four wire low voltage distribution system supply large number of power to single-phase load, because some load produces large 3-order harmonic current (zero sequence), 3-order harmonic in three-phase circuit is added in the neutral line, which may make the neutral current reach 1.7 ~ 2 times phase current, and the cross-sectional area of the neutral conductor and conductor is same, so cause the neutral line serious overload.

d. Effect on power loss

Harmonic is over-draught on power systems and user equipments cause additional loss. Harmonic power itself can be said loss completely, thereby increase the network loss.

Harmonic will not only reduce the efficiency of distribution network and the electric equipments as to cause failure, shorten life, but also will cause exchange of the distortion power between the power network and electrical equipment, which will increase apparent power and reduce power factor, and increase the network loss of power system and reduce the utilization efficiency of electric energy. Recent studies show that harmonic suppression can improve the power supply quality and at the same time have a certain energy saving benefit[11][12][13], based on previous research this paper analyze economic benefits of the harmonic distribution network, combing with the example through simplifying theoretical calculation, verified the validity and practicability of whole analysis.

II.   POWER SYSTEM HARMONIC THEORY

"Harmonic" stems from the concept of acoustics, said a string or a column of air and the circular frequency multiple and frequency vibration. Introducing the concept into electricity, definition of harmonic of the international IEEE standard says: "harmonics is a periodic wave or component sine wave, the frequency is an integer multiple of the fundamental frequency". J.B. Fourier proposed that Fourier analysis was an effective method to study and analyze the harmonic distortion. In general any periodic wave form can be expanded in Fourier series, the periodic distorted current are expanded into Fourier series as follows[14][15][16]:

$$i(t) = \sum_{h=1}^{M} I_h \cos(h\omega_o t + \theta_h) \qquad (2\text{-}1)$$

In this equation, I_h means the peak current of h order harmonic; Q_h means the peak current phase of h order harmonic, ω_o is the fundamental frequency; M is the highest number for consideration of harmonic, generally taking 50 order.

From the $\quad I^2 = \dfrac{1}{T}\int_0^T i^2(t)dt = \sum_{h=1} I_h^2 \qquad (2\text{-}2)$

Total root mean square value of the current is expressed as:

$$I = \sqrt{\sum_{h=1}^{M} I_h^2} \qquad (2\text{-}3)$$

Usually using the harmonic ratio and the total harmonic distortion to measure the total size of harmonic component and distortion degree of the waveform, this is defined as follows:

Percentage content of h order harmonic current:

$$HD = \frac{I_h}{I_1} \times 100\% \qquad (2\text{-}4)$$

Total distortion rate of harmonic current:

$$THD = \frac{\sqrt{\sum_{2}^{M} I_h^2}}{I_1} \times 100\% \qquad (2\text{-}5)$$

Equation (2-1) to (2-5) are total root mean square values of the current, I_1 is root mean square value of the current as the fundamental current, I_h is root mean square value of the h order harmonic current.

For the analysis of harmonic voltage, only need to modify the current variable to voltage variable.

AC parameters of power components is associated with the frequency, harmonic frequencies are integer-multiples of the fundamental frequency, so the harmonic parameters components are different with fundamental AC parameters of power components.

Under the function of high order harmonic component, the resistance and inductance of transmission line has skin effect, and impedance per unit length is:

$$Z_l = R_{dc} \cdot \alpha_R + 2 \times 10^{-7} jn\omega_1 \ln\left(D_{eq} \cdot e^{\alpha_L} / r^{'}\right) \Omega / m \quad (2\text{-}6)$$

In this equation, R_{dc} is resistance of DC circuit per unit length (W/ m); D_{eq} as the geometric mean distance of three-phase wire (m); $r^{'}$ is geometric average radius of the line (m); α_R is coefficient of skin effect of line resistance. If we ignore the skin effect when at fundamental frequency, standard value of full length R and X of transmission line when n order harmonic occurs would be as follows[17][18]:

$$R_{LB} = R_{sB} \cdot \alpha_R$$
$$X_{LB} = nX_{sB} + 2 \times 10^{-7} n\omega_0 \alpha_L' s / Z_B \qquad (2\text{-}7)$$

In this equation, S is the length of transmission line (m), Z_b is the reference value of impedance (Ω), R_{sb}, X_{sb} is standard value of full length R and X at a given frequency. Line admittance generally lineally varies with the harmonic frequency.

Under the function of high order harmonic component, magnetizing branch of transformer is negligible, capacitor between the voltage transformer windings and the winding inter turns will play a role, the harmonic impedance can be expressed as

$$Z_{Tn} = nR_{T1} + jnX_{T1} \qquad (2\text{-}8)$$

It is generally believed that the characteristics of shunt capacitors and shunt reactors have desirable linear characteristics, that are the capacitor $B_n = nB_1$, reactor $X_n = nX_1$.

Potential of the generator is a pure sine wave, without containing high order harmonics. Asynchronous motor can be regarded as constant impedance; the equivalent harmonic impedance is as follows:

$$Z_n = nR_1 + jnX_1 \qquad (2\text{-}9)$$

In this equation, R_1 and X_1 is resistance and reactance of fundamental wave.

III. ANALYSIS OF HARMONIC LOSS

Harm to power system harmonic caused is to increase the network loss, harmonic loss is the main heat loss of harmonic currents in power transmission network, it is affected by harmonic resistor, capacitor, and reactor would have little power loss.

For high, medium voltage lines, there is generally no neutral line, only need to consider the resistance loss of three-phase line caused by harmonics, which can calculate the total harmonic power loss with the following approximate method [2].

$$P_h \approx 3 \times (THD_I I_1)^2 R_h = THD_I^2 (\frac{R_h}{R_1}) P_1 \qquad (3\text{-}1)$$

In this equation R_h is the equivalent harmonic impedance, according to the measured harmonic content data, taking weighted average of each harmonic resistance. Skin effect and proximity effect of the line harmonic wires will decrease the effective cross-sectional area of conductor and increase harmonic resistance, and increase the loss of line.

Three-phase four wire system wiring is adopted by low pressure systems in general, including loss in three-phase lines, and the neutral line loss. Harmonic loss of neutral line express as:

$$P_{hN} \approx (\frac{R_{hN}}{R_{1N}})(THD_{I0})^2 P_1 = (\frac{R_{hN}}{R_{1N}})(\frac{THD_1}{C})^2 P_1 \qquad (3\text{-}2)$$

When phase current harmonics contain takes 3N order harmonic current as dominant, C = 1/3, and while takes non 3N order harmonic current as dominant, and less zero sequence harmonic current, C value would be great.

Harmonic loss of transformer is determined by the harmonic current and voltage, satisfying the following relationship [5] [6] as follows:

$$P_h = \sum 3I_n^2 R_n + P_0 \sum (\frac{V_n}{V_1}) \frac{1}{n^{2.6}}$$
$$\approx (\frac{R_n}{R_1})THD_I^2 P_{cu} + P_0 (\frac{1}{n^{2.6}})THD_V^2 \qquad (3\text{-}3)$$

In the formula, V_n and I_n is the harmonic components of voltage and current respectively of n order harmonic, R_n is the n order harmonic copper loss resistance of transformer; R_n is the equivalent harmonic impedance; P_o is power loss of fundamental wave at empty load. As can be seen, with the increase of current distortion rate of harmonic, harmonic loss of transformer would increase, and the efficiency of transformer would be lower.

Harmonic loss of the motor is similar with transformer, when harmonic voltage is larger, the magnetic saturation will decrease harmonic reactance and harmonic resistance, the total harmonic loss would increase. The literature[7] shows that when variable frequency power supplies, the iron loss of motor increased 10%-20% compared with power supply, and high frequency copper loss of stator was 15% of power supply copper loss, while copper loss of the rotor is approximately equal to power supply copper loss of rotor. Due to the influence of power harmonics, fixed loss of the motor increase about 30%, this will cause the motor efficiency decrease about 2%.

IV. A CASE STUDY

The electricity consumption of world data center in 2010 is about 1.1% to 1.5% of the total generating capacity of whole world in 2010, while the main load of data center are harmonic source equipment containing power electronic devices such as air conditioning, water pump, and the operation and maintenance department are very concerned about the energy conservation and efficiency improving[19][20][21].

The research and harmonic test of a data center in our country previously, helped us to understand that the company was supplied by two 10kV power, the annual electricity consumption was about 8700000 degrees, through the two main transformer, the voltage was reduced to 380V, and the transformer adopted D/Y11n wiring mode, electric equipments of companies were all at the 380V side, internal distribution circuit adopted three-phase five wire system, and taking the main harmonic source like cold water unit and chilled water pump in device as the test points, and then the test data of harmonic in the three-phase line and midline were handled as shown in table 1.

GB "harmonic of public power network" proves [8] that voltage distortion rule of 380V voltage class rate is less than 5%, odd and even order harmonic voltage ratio is less than 4% and 2% respectively, the connection mode of distribution transformer is D/Y11n, and 3 order harmonics on 380V lateral line will not transfer to the high voltage side, through the measured data, we can find that voltage ratio and the total harmonic distortion of each order harmonic basically meets the requirements. Then measurement results of harmonic test are used to analyze harmonic loss of internal line and energy efficiency of company.

TABLE.1 HARMONIC TEST RESULT OF A DATA CENTRAL

Test point	Voltage Harmonic Distortion (%)				Current Harmonic Distortion (%)			
	THUD	3	5	7	THUD	3	5	7
Phase A of Chiller	2.5	0.2	1.4	1.0	3.3	0.6	1.5	2.7
Phase B of Chiller	2.4	0.3	1.1	1.1	3.4	0.4	1.5	3.0
Phase C of Chiller	2.5	0.2	1.3	1.0	3.4	0.2	1.7	3.0
Phase N of Chiller	128.4	51.8	5.6	23.3	11.9	9.3	1.3	3.1
Phase A of chilled water pump	5.3	0.7	3.3	3.8	44.6	36.5	7.3	16.2
Phase B of chilled water pump	4.3	0.9	1.7	2.9	55.4	33.3	8.3	13.4
Phase C of chilled water pump	1.3	0.1	0.5	0.6	50.9	30.7	4.5	13.4
Phase AN of chilled water pump	198.1	86.4	3.7	114.9	95.7	73.5	16.5	32.7

Note: the active and apparent standard of the neutral point of chilled machine and water pump marked is their own total power.

Simplifying the calculation and getting the line resistance coefficient of skin effect α_R was 1, while ignoring the influence of harmonics in the distribution transformers and motors, if harmonic energy consumption from such conservative assessment is large, the harmonic energy saving scheme would be feasible.

Without considering the neutral line, according to above analysis, the relationship between loss of the three-phase line and harmonic loss and the fundamental wave loss is:

$$P_1 = 3 \times (I_f^2 + I_h^2)R = 3I_f^2R + 3I_h^2R$$
$$= P_f + P_h \tag{4-1}$$

And the ratio harmonic loss on three-phase line accounts for total line loss is:

$$\frac{P_f}{P_1} = \frac{3I_h^2R}{3I_f^2R + 3I_h^2R}$$
$$= \frac{THID^2}{1 + THID^2} \tag{4-2}$$

The measurement data shows, total harmonic distortion of the three-phase line current is 55.4% at largest, and usually the line loss rate is about 5%, and then got that harmonic loss rate of a three-phase line in the factory is less than 1%, that means annual energy-saving 87000 degrees ideally could be achieved through harmonic suppression.

In the distribution network with mid-line, the loss of three order harmonics in the line is largest, component of the other order harmonics in the midline is negligible, in this case the relationship between loss of the line and harmonic loss and the fundamental wave loss is:

$$p_1 = 3I_f^2R + 3I_h^2R + 9I_{3h}^2R$$
$$\approx 3I_f^2R + 12I_h^2R \tag{4-3}$$

And the ratio harmonic loss of line containing mid-line accounts for total line loss is:

$$\frac{P_f}{P_1} = \frac{3I_h^2R + 9I_{3h}^2R}{3I_f^2R + 3I_h^2R + 9I_{3h}^2R}$$

$$\approx \frac{4THID^2}{1 + 4THID^2} \tag{4-4}$$

The measurement data shows, total harmonic distortion of the N line current is around 95.7%, and the line loss rate is thought about 5%, and then got that harmonic loss rate of the line in the factory is about 1% at most, that is 4 times total harmonic loss without considering mid-line. Theoretically 334000 degrees would be saved annually through the suppression of 3 order harmonic on mid-line[22][23][24].

V. CONCLUSION

The above analysis shows that, the harmonic has different influence on the power lines, electric motor and transformer power, the larger harmonic distortion rate is, the larger energy consumption caused would be, eliminating harmonics can improve power quality at the same time bring certain economic benefits. Energy consumption caused by harmonic in distribution network is most obvious in three phase four / five wiring mid-line, through case study, around 4% electricity would be saved through completely eliminating 3 order harmonic in mid-line. But for its economic benefit we need to consider harmonic control cost, and power loss of filtering device, if there would some electricity left which is saved through harmonic suppression after making up the loss mentioned above, which means that if the cost of harmonic suppression is not more than the electricity fee saved, the harmonic energy saving scheme would be feasible[25][26][27].

In order to reduce the harmonic pollution, the following measures can be taken from the Power Grid Corp level:

In order to ensure the power quality of power network will not deteriorate further, reducing the harmonic pollution of power grid, ensuring the safe and stable operation of power system, should follow the principles such as "polluter governance" and "preventing new pollution and handling with previous pollution", implement the policy "prevention first, combining prevention with controlling". Power supply company and power quality supervision institutions at all levels should supervise and actively cooperate with the users of electricity pollution prevention and treatment work, through

entire project "designing, construction, acceptance". After managing the grid can be "purified", the user can save energy and decrease loss, achieve a win-win objective.

When new capacitor, filter are in the design phase, selecting series reactor in accordance with the corresponding procedures, and checking parallel resonant point of power network and the harmonic amplification multiple in different operation modes.

When power grid construction, design or operation mode changes, power system design and operation department should be responsible for checking the problem of accounting harmonic effect, to prevent the filter, capacitor causing amplification of resonance or harmonic.

Giving priority to use D/Yn11 distribution transformer for construction and transformation of distribution network, in order to reduce the harmonic transferred from distribution network to higher voltage level power grid. For bus whose three-order harmonic voltage exceeding the standard caused by operation of Y/Yn0 distribution transformer, 3 filters should be installed.

Suggestions:

1. Installing AC filter device, provided with several single tuning and high pass filter nearby harmonic source, to absorb harmonic current;

2. Changing the configuration or working way of interference source, focusing devices with interfering complementary, or these devices should be appropriately distributed or used alternately, and working way with large interference should be limited appropriately;

3. Avoiding capacitor amplifying harmonic, changing series reactor of the capacitor, or changing some by-pass of the capacitor group into filter, or limiting the input capacity (group number) of the capacitor

4. Adopting equipments such as active filter and static idle generator and so on can effectively filter harmonic.

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