Real Time Power Factor Correction in Industrial Plants with Non-Linear Loads

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Abstract — **Non-linear loads generate current harmonics in the electric power system of industrial plants. These loads also contribute to reduce the power factor. As one knows, if capacitors are installed for power factor correction, parallel resonance may occur and this may cause over-voltages in electric power lines. To avoid resonance, harmonic filters are commonly used. This article describes a research work that is being carried out with the purpose of using a data acquisition and control system and a radio-frequency apparatus for adaptively correct the power factor without the need for harmonic filters.**

Index Terms — **Power factor correction, harmonic control, harmonic load-flow analysis, frequency-hopping spread spectrum, wireless communication.**

I. INTRODUCTION

Large industrial plants like paper and metal industries have in their electric power system a large amount of non-linear loads. These loads generate current harmonics in the electric power lines and contribute to reduce the power factor in the bus bars they are connected to as well as in the whole system. The installation of shunt capacitors is a traditional method of correcting the power factor. However, using this method in plants with non-linear loads can bring forth the phenomenon of parallel resonance. Typically some previous analysis is carried out to verify if resonance can occur. This analysis is made based on the topology of the circuit and on the harmonic content in various points of the electric power system. This study is known as harmonic load flow analysis and it determines the order, magnitude and phase of the harmonics that produce the resonance. Then, blocking inductors are installed in series with the capacitor banks, creating filters that eliminate the current harmonics responsible for resonance. This is the usual method.

This work describes a research activity that is being carried out at INATEL. This research aims at developing a system for power factor correction using exclusively capacitors, without the need for filters. This will be made through the correct choice of the capacitors to be switched on or off for simultaneously correcting the power factor and avoiding parallel resonance. This choice is made based on an analysis of the topology of the electric power system and on measurements of its harmonic content, both in real time.

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II. THE SOFTWARE OF THE SYSTEM

Fig. 1 shows a simple electric power system diagram containing one main station, two secondary stations and linear and non-linear loads powered by these secondary stations.

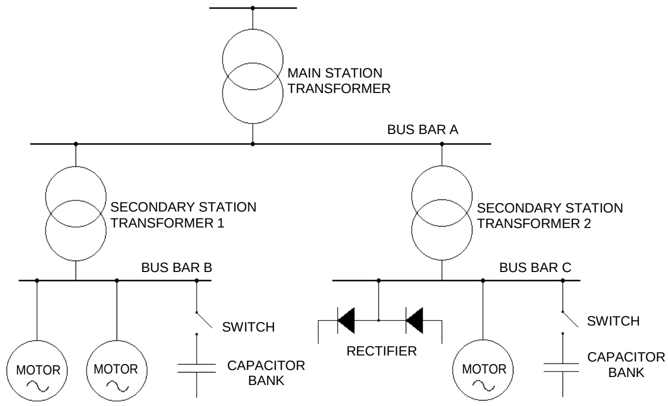

Fig. 1. Electric power system example.

Referring to Fig. 1, at the main station will be installed a central processing unit (personal or industrial computer) containing:

1. The system configuration with technical information from bus bars A, B and C (cable and transformer data) and from the loads powered by the bus bars B and C.
2. A software that, given the data mentioned on the preceding item, given the real-time current and voltage measurements obtained from bus bars B and C, will estimate the present equivalent circuitry of the sub-system.
3. A software that, given the current measurements from bus bars A, B and C, will allow, in real time, the determination of the harmonic content on those bus bars. This content encompasses the order, magnitude and phase of the harmonics.
4. A software that, given the power factor calculations for bus bars A, B and C, and given the target power factor for the whole plant, will calculate the amount of reactive power to be inserted in the system to reach that target.
5. A software that, given the information in the preceding items, will simulate the switching of the capacitor banks on bus bars B and C to maintain the target power factor. The occurrence of parallel resonance will be verified based on the present circuitry topology, based on the harmonic content and based on the information about the capacitors that must be switched on. The simulation goes on until the determination

of the necessary amount of capacitors to be inserted into the system, and their respective places of insertion, in a way that no resonance occurs and the power factor is corrected. At this moment, commands for the actuation (switching on) of the capacitors will be sent to the places previously determined.

The modeling of the equivalent circuit of the plant and the calculations related to the determination of the power factor will be based on one's experience and on well knows procedures [3] - [9] and on the references therein.

It is also very important to mention that the switching of capacitor banks is a very sensitive electric operation, since the switches are severely stressed during the switching process. Due to this fact, the commands for actuation of the switches take into consideration that the target power factor refers to an average value, calculated during periods of, typically, one hour.

III. The Present Status of Software Development

As one can conclude from the preceding description, the simulation described aims at predicting the occurrence of resonance, before sending the commands to the actuators of the capacitor switches. On the following paragraphs, we describe the process of prediction.

Fig. 2 shows a bus bar of an electric power system and the loads connected to it. This is a typical situation in which parallel resonance may take place if the capacitor bank is switched on to correct the power factor.

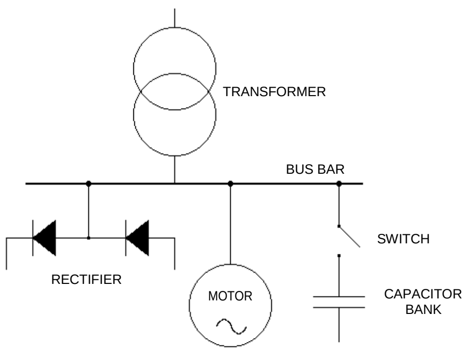

Fig. 2. An example of a typical loading on a bus bar of an industrial plant.

The equivalent circuit for the system shown in Fig. 2, valid for the *n*-th harmonic, is shown in Fig. 3. This circuit allows for the verification of resonance occurrence for this *n*-th harmonic. In the circuit shown in Fig. 3 the rectifier (converter) is represented by a current source.

The number of circuits to be simultaneously analyzed is equal to the number of harmonic orders considered. As an example, if the most important harmonics to be considered are those of orders 5, 7, 11 and 13, four circuits must be analyzed, one for each harmonic order.

At the moment, the research carried out has already yelded:

1. The equations that, for the main loads, allow the equivalent circuit to be implemented in real time;

2. A software for analyzing the harmonic content in real time (under development).

It still remains to be implemented:

1. The software for obtaining the topology of the system and the parameters of the equivalent circuits;

2. The software for analyzing the parallel resonance.

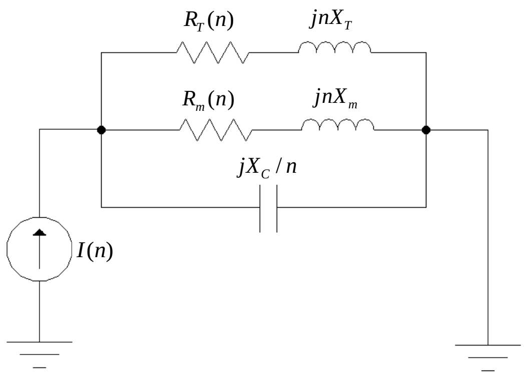

Fig. 3. Equivalent circuit for the situation shown in Fig. 2.

Where:

$I(n)$: value of the *n*-th order harmonic.

n: order of the harmonic.

$R_T(n)$: resistance of the equivalent circuit for the transformer, evaluated at the fundamental frequency ($n = 1$).

$R_m(n)$: resistance of the equivalent circuit for the motor, corrected for the harmonic of order n.

X_m: reactance of the equivalent circuit for the motor, evaluated at the fundamental frequency.

X_c: reactance of the equivalent circuit for the capacitor bank, evaluated at the fundamental frequency.

IV – The Control System via RF

All the voltage and current measurements from the electric power system lines and bus bars will be made by a data acquisition (DAQ) system. The acquired data will be sent to the central processing unit via radio frequency (RF) signals. The commands for actuation of the capacitor switches will also be sent via RF signals. Fig. 4 shows the topology of the proposed control system.

At the main station will be installed a computer (industrial PC, for example) where all the software routines to be developed will be loaded and will run. These routines will be responsible for controlling the hardware devices, processing the collected data and sending commands for switching the capacitor banks on and off, in a way that the power factor is maintained in its target value. The programming language we are using is LabVIEW, from National Instruments. All the hardware related to data acquisition and data transmission are also from National Instruments.

The signals collected at the measurement points are multiplexed in a way that they share a unique channel of the DAQ board (if the number of points is larger than the number of channels of the DAQ board). Each pair formed by one multiplex and one data acquisition board is mounted on an equipment called SCXI (Signal Conditioning eXtensions for Instrumentation). The SCXI devices are connected, via RS-232 interface, to radio-modems operating with Frequency Hopping Spread Spectrum (FH-SS) technique. This technique has great immunity to interference [1] and certainly will turn the communication feasible and reliable in the noisy industrial environment. This idea also brings with it a reduction in installation time and in the number of problems that occur when similar wired control systems are implemented.

The radio-modems installed close to the measurement points in the plant (slave radios) will transmit the results of measurements to the radio installed at the main station (master radio). These slave radios will receive, from the master radio, control data to command the switching of the capacitor banks.

In those cases where the distance or another bad RF signal propagation condition deeply attenuate the received signal, in a way that the direct communication between the master and a slave radio or vice-versa is not possible, a repeater can be inserted between them to make communication feasible.

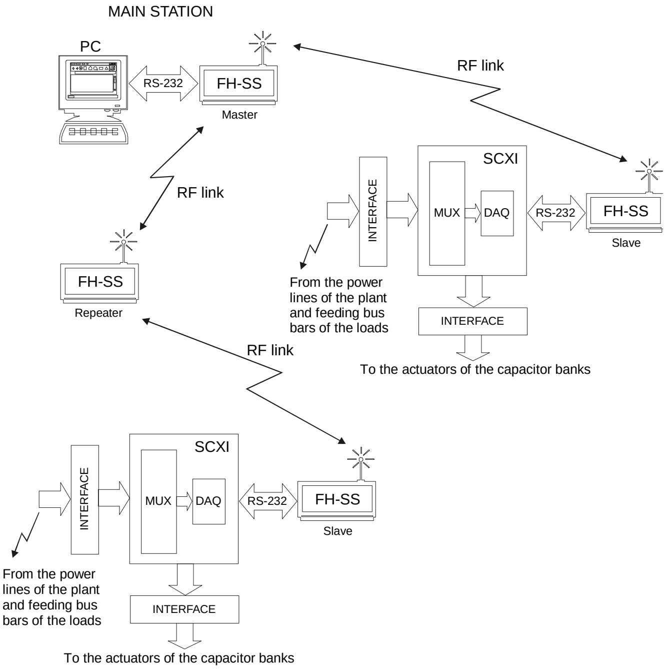

Fig. 4. Topology of the proposed control system.

The interfaces between the SCXI modules and the power and feeding lines are necessary for sensing and conditioning the high voltage and high current signals for data acquisition. The interfaces between the actuators and the SCXI modules are necessary to adapt the signals from the output channels of the DAQ board to the actuators to be used.

Related to the routine for harmonic content analysis in the electric power system of an industrial plant, the use of Joint Time-Frequency Analysis (JTFA) [2] is our proposal. This analysis leads to a precise monitoring of the temporal variations of the harmonic content in the plant. Our starting point has been an adapted version of a JTFA application developed by National Instruments. The facilities of this application can be visualized in Fig. 5. The graph on the lower part of Fig. 5 shows a 60 Hz signal that, between the instants 1 and 4 seconds, were corrupted by harmonics of order 2, 3 and 4. Given the small values of the harmonics added, there is no possibility of noting this contamination in time domain. Also, the frequency domain analysis alone can not identify the spectral variations over time. However, these variations can be observed in the graph on the upper part of Fig. 5, the so called spectrogram of the analyzed signal. From the spectrogram, one can easily see the appearance of the corrupting harmonics at the instant 1 second and their vanishing at the instant 4 seconds. The magnitude of the spectral components at each time instant can also be obtained from the graph on the right part of Fig. 5, the instant spectrum.

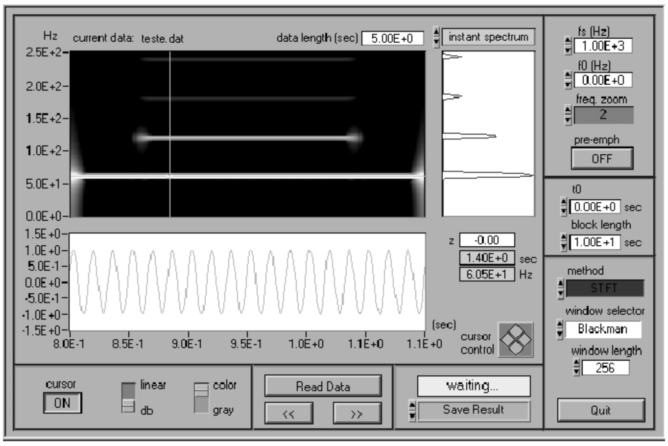

Fig. 5. User interface of the JTFA application from National Instruments.

IV.1 – Spread Spectrum Signals

Spread Spectrum (SS) technique is known to have been used for a long time in many applications. Its first use was in military communication systems [1] and, since then, it has been used also for civilian communication systems like CDMA (Code Division Multiple Access) cellular telephony.

A spread spectrum signal is a signal that occupies a bandwidth a number of times larger than the necessary one, independently on the bandwidth of the original signal [1]. A signal that occupies a bandwidth greater than the information rate not necessarily configures a spread spectrum signal. This case occurs, for example, in low bandwidth efficient modulation schemes.

Among the main characteristics of Spread Spectrum technology are:

1. Interference rejection;
2. Possibility of implementing multiple access techniques;
3. Robust against multi-path propagation;
4. Low probability of interception;
5. Security.

There are two basic forms of generating a spread spectrum signal: by direct sequence spreading and by frequency hopping spreading. A Direct Sequence Spreading Spectrum (DS-SS) signal can be generated through multiplication of a bipolar {+1,-1} information signal by a Pseudo Noise (PN) sequence, also bipolar. The resulting signal modulates the carrier, typically in phase (PSK, Phase Shift Keying) [10]. This process is illustrated in Fig. 6 (a). The DS-SS signal can also be generated through modulo 2 addition between the unipolar {0,1} information signal and the PN sequence, also unipolar, followed by the carrier modulation process. This is illustrated in Fig. 6 (b). The rate of the PN sequence is greater than the information rate, the quotient between them representing the so called Processing Gain of the spread spectrum system [1]. The Processing Gain establishes the improvement in performance of a spread spectrum system compared to a non spread spectrum one, when interference is present. The greater the Processing Gain, the more immune to interference is the spread spectrum system.

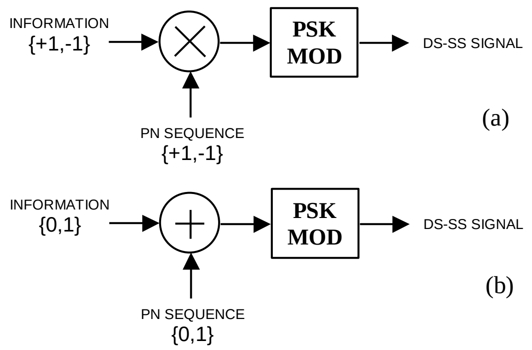

Fig. 6. Implementation of a DS-SS signal
(a) by multiplication and (b) by modulo 2 addition.

A Frequency Hopping Spread Spectrum (FH-SS) signal is generated by direct modulation of the carrier by the information sequence, normally in frequency (FSK, Frequency Shift Keying) [10]. The carrier frequency is generated by a synthesizer controlled by a PN sequence generator. This process can be seen in Fig. 7. If the rate of the PN sequence is greater than the information rate, the carrier frequency jumps several times during one information bit, and in this case it is said that we have implemented a Fast FH-SS system. Instead, if the PN sequence has a rate slower than the information rate, a Slow FH-SS system is implemented.

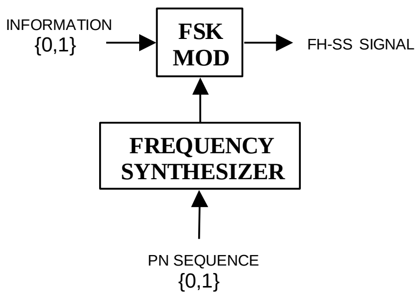

Fig. 7. A process of generating a FH-SS signal.

IV.2 – Performance of the FH-SS Radio-Modems

Chapter 6 of [1] presents an extensive study on the performance of Direct Sequence and Frequency Hopping spread spectrum systems operating under interference. The intentional interferences (jamming signals) analyzed in [1] are:

1. Barrage noise jammer;
2. Partial-band noise jammer;
3. Tone jammer;
4. Multiple tone jammer;
5. Pulsed noise jammer;
6. Follower or repeater jammer; and
7. Smart jammer.

Regarding FH-SS communication systems, the interferences numbered 6 and 7 above are the most effective in degrading the communication, but fortunately these interferences are not generated in the industrial environment we are considering in this paper. The follower or repeater jammer generates a narrow band signal that jumps following the same PN sequence used by the communication system. The smart jammer adapts its signal to the transmissions generated by the communication system in a way that the degradation in the communication is maximized.

Among the first four types of interferers cited above, the partial band noise jammer is considered to be the most efficient in degrading the performance of FH-SS communication systems [1]. This jammer is generated by filtering an AWGN (Additive White Gaussian Noise) signal. The resulting rectangular shaped spectrum for the partial band noise jammer leads to roughly the same performance degradation as the Gaussian shaped one [1]. However, the former can not be realized and the later can be used for a real field or bench test. Also, there exists an optimum relation between the bandwidth of the FH-SS signal and the partial band noise jammer, in a way that the performance degradation of the communication system is maximized. This relation depends on the ratio between the average signal power and the average jamming power [1].

Fig. 8 shows the power spectrum (one hop) of the FH-SS signal irradiated by the radio-modem we are using. Also in Fig. 8 one can see the partial band noise jammer with a Gaussian shaped power spectrum. This jamming signal was created using the software WinIQSim™, developed by ROHDE & SCHWARZ, and synthesized using the SMIQ 04B signal generator, also from ROHDE & SCHWARZ. The jamming signal was inserted between two radio-modems, in one of the links. In Fig. 8, the width of the screen shown spans roughly the whole band available for the jumps of the FH-SS signal (about 26 MHz).

A bit error rate (BER) measurement was realized according to the situation described above and we found, as expected, an improvement in performance as compared to the theoretical results presented in [1]. This better result was attributed to the error correction procedure used by the radio-modems. A CRC (Cyclic Redundancy Check) is used for error detection and an algorithm for retransmission reduces the average bit error rate. The algorithm works causing a retransmission whenever a high interference is detected during a frequency hop. The packet transmitted during this interference condition is retransmitted on the next hop. This process obviously reduces the data throughput, but this is not so relevant in our implementation, since the actualization rate of the status of our control system is relatively slow, occurring once per hour. However, the performance verified for the radio-modems is expected to make our system feasible and efficient in the noisy industrial plant. Our next step is to test the performance of the radios in a real industrial plant. We expect that the performance in this case will be better than that obtained with the partial noise jammer.

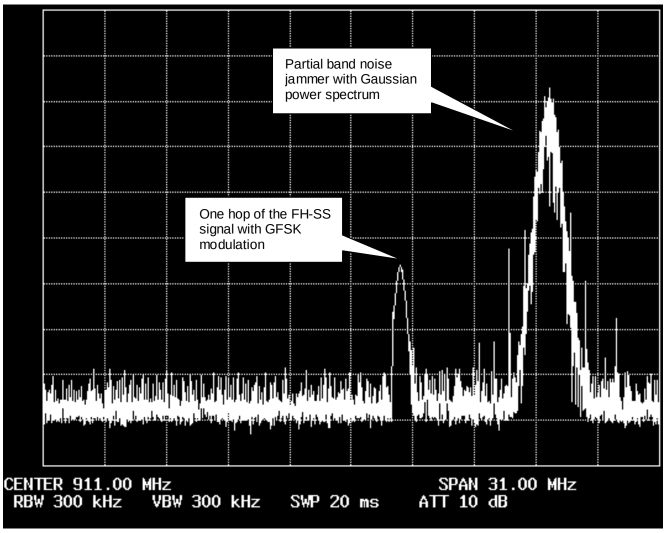

Fig. 8. Power spectrum of a FH-SS signal corrupted by a partial band noise jammer.

V – Summary and Concluding Remarks

Low values for the power factor in industrial plants can lead to the following main problems:

1. Overload in transformers;
2. Unacceptable voltage drops;
3. Legal penalizations by the energy supplier company;

The usual method for power factor correction uses banks of capacitors in strategic points in the plant. But with non linear loads, such as static converters and arc ovens, such method can cause over-voltages due to parallel resonance. The localization and switching of the banks must then be carefully made, according to the variations in the load. Nowadays, if the possibility of parallel resonance exists, expensive blocking inductors are installed in series with the banks of capacitors to eliminate the harmonics that cause resonance.

The research work presented in the paper aims at developing an appropriate control system for plants where non linear loads can lead to parallel resonance. A software, installed in a central processing unit, will receive signals from various points in the plant and calculate the power factor, the harmonic content of the current, the topology of the equivalent circuit and the number of capacitors switched on or off. If the software detects the need for correcting the power factor, it will simulate the behavior of the power factor correction process and determine the most appropriate point to insert capacitors in a way that no resonance occurs, before doing it. Using this method, there is no need for using blocking inductors and the correction of the power factor process is optimized.

The signals acquired in the field by data acquisition devices, and the control commands sent back to the actuation points will be transmitted to and from the central station via spread spectrum signals. This technique has great immunity to interference and was chosen to make the communication feasible in the very noisy industrial environment. The use of radio signals also brings the relative reduction of the problems and the time spent when similar wired systems are installed.

Our idea started as a student project, but has grown and is now a candidate for a part of an M.Sc. dissertation work and, in the future, of a Ph.D. thesis. The first implementations, the tests with the remote data acquisition system and the tests with the radio-modems are motivating us and showing us that we are on the right path. We also implicitly showed in this work a junction between wireless communication and industrial control systems, an association that is considered promising by many researchers.

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