

# Applications of Real-Time Simulation Techniques for Harmonics Study of An Industrial Power System

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**Abstract-** Due to the increasing use of nonlinear loads, the associated power quality (PQ) problems have become a major concern to many electric utilities and their customers. For efficient and accurate analysis, the performance of computer simulation has been recognized as an important and necessary procedure to the power quality study. With the advanced development of computer and communication technologies, the real-time simulation becomes matured and provides better computational efficiency, flexible and scalable programming, and preserves a preciseness as good as conventional off-line simulation. This paper presents an application example of real-time simulation to harmonics study of an industrial power system. A cluster-based real-time simulator is executed under MATLAB/SIMULINK environment, where an industrial power system including the arc furnace and motor drives, as well as PQ mitigation devices is under test by real-time simulation techniques. In addition, the conventional off-line simulation with variable-step solver is included to compare the performance of the real-time simulation. Results indicate that the real-time simulation has a great advantage in both the computational efficiency and the system size under study than the off-line simulation, while the solution accuracy is maintained.

**Index Terms-** Nonlinear load, power quality, real-time technique, harmonics

## I. INTRODUCTION

IT is known that simulations are an essential way in the development and problem-solving for power system studies. With the rapidly growing on information technology (IT), several commodity-off-the-shelf (COTS) off-line digital simulation tools, such as MATLAB/SIMULINK, EMT/ATP, PSCAD/EMTDC, PSPICE/ORCAD, and LABVIEW are widely available in power engineering study. However, the disadvantages are produced while implementing off-line simulations performed by such tools may be time-consuming and numerically instable, and lack the capability of interfacing with real devices. A real-time simulation is therefore gradually adopted to replace off-line simulation without the mentioned drawbacks. The significant requirement of the real-time simulation is to ensure that the calculation for a time-step is accomplished within the chosen step-size. To perform the real-time simulation for harmonics studies, it is essential to combine computer hardware with efficient software for parallel computation [1].

In the study MATLAB/SIMULINK and its SimPowerSystems Blockset (SPS) toolbox are chosen to perform the real-time simulation. SPS offers adequate algorithms in solver engine, which includes fixed-step and

variable-step methods, for the user to select to solve the problem model. However, the fixed-step method is often used in the real-time simulation technique because of its computational efficiency. Despite the fact that SPS supports a fixed-step solver based on the Tustin method, SPS alone cannot satisfy the demands in real-time simulation due to some limitations [2]. In the study a software toolkit add-on for SPS called Advanced Real-Time Electro-Mechanical Simulator (ARTEMIS) [3] is introduced to overcome the aforementioned limitations for real-time simulation. To create a distributed real-time platform, the software RT-LAB running on the QNX operating system is also included in this paper [4], where RT-LAB is a scalable simulation and control package that built in SIMULINK and provides a simple separation of the system model into subsystem models for the execution of parallel simulation.

In the studied power system, there are several nonlinear loads, such as electric arc furnace (EAF) and adjustable speed motor drivers, and harmonic currents are being injected into the system and cause voltage distortions. To study the impact of the PQ disturbances caused by the nonlinear loads, the real-time simulation for studying the PQ problems are implemented and results are reported.

## II. IMPLEMENTATION OF A CLUSTER-BASED REAL-TIME SIMULATOR

Based on the combination of ARTEMIS and RT-LAB, a cluster-based real-time parallel simulator is performed on COTS PC platform that practices self-acting conversion of SPS schematics into real-time simulation. For a large and complicated power system model, the adopted simulator also provides a distributed technique to achieve parallel computation on a PC with single, dual, or quad CPUs. The configuration of the cluster-based real-time parallel simulator is shown in Fig. 1, where two groups of computers, *target cluster* and *host*, are included in simulator. Moreover, the external hardware also can be included for the hardware-in-the-loop (HIL) simulation, if necessary.

### A. Hardware and Software Architecture for Target Cluster

With the use of real-time simulation, there is one cluster node acting as a master and the other nodes acting as slaves. The master is mainly used for managing the communications between host and each target node. And the tasks of slaves are mostly emphasized on computational purposes. The target cluster nodes can be arbitrarily assigned by users to determine the master and the slaves. The PC with multi-core processors is used to replace multiple single-processor PCs to be the target clusters in the study; for instance, Intel® Core™ 2 Quad 2.4 GHz CPU with a 1.0 GB memory COTS PC is available for target cluster. Four target nodes (one for master and three for slaves) are assigned in a Quad CPU.

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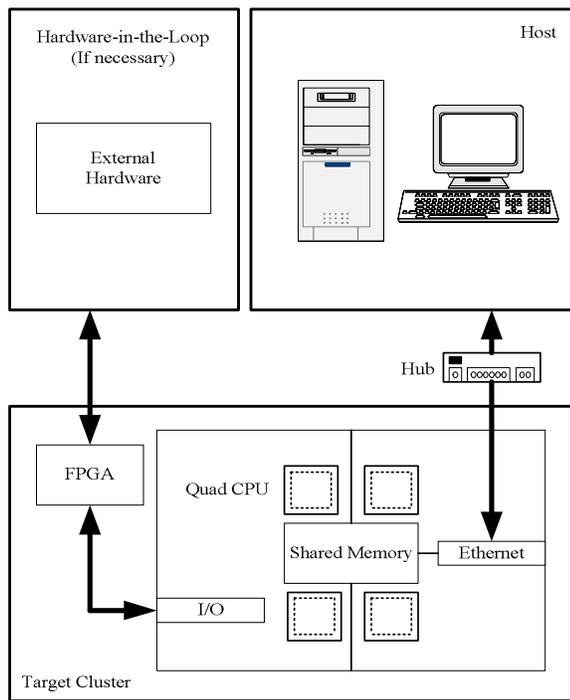


Fig. 1. A Cluster-Based Real-Time Parallel Simulator.

A real-time operating system (RTOS) is required for running the target cluster. RTOS provides a multitasking operation intended for real-time applications that also makes simulators more efficient and flexible. An open-source RTOS called QNX [5] is chosen for giving an efficient performance on the target cluster in study.

### B. Hardware and Software Architecture for Host

In real-time simulations, the tasks of hosts are used to be a console or a command station for controlling and monitoring the processes of computations. Usually, the implementations of model developments, compilations and code loading to target clusters are executed in hosts. A single computer or a group of computers are in general to be the host in real-time simulations. Besides, HIL is performed by using external hardware to be the host and often connected with target cluster by a FPGA-based I/O card. In the study, a single computer is used to be the host that has an Intel® Core™ 2 Duo 1.86 GHz CPU with 1.0 GB memory.

For running the host, Windows XP is adopted as an operating system. A construction of the real-time simulator is achieved in the MATLAB/SIMULINK environment. The SPS blockset built-in SIMULINK provides an efficient development at the beginning of power system models. In real-time simulation, it is necessary to overcome the limitations of using variable-step solver and built-in fixed-step solver in SPS. The software ARTEMIS is also included in the host that uses a high-order fixed-step integration algorithm which is not prone to numerical oscillations, and advanced computational techniques are necessary for the power system real-time simulation in the study. An interfacing software, RT-LAB, developed by OPAL-RT® is used as a communication between the target cluster and the host. RT-LAB plays an important role which is a distributed real-time platform that encourages the design

process for systems by taking users from SIMULINK models to real-time even with HIL, in a short time and at a low cost. The software information flow of the performance of the real-time simulator in the study is depicted in Fig. 2.

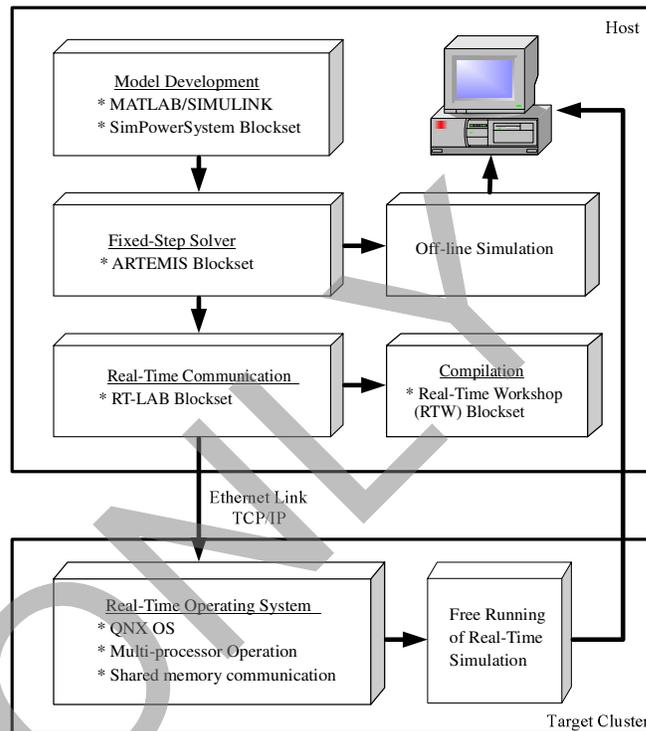


Fig. 2. A Cluster-Based Real-Time Parallel Simulator.

### C. Communications

It is necessary to ensure an effective communication existed between the target cluster and the host. There are several types of communication techniques are used in study.

**i) Fast Ethernet Link:** Ethernet is a family of computer networking technologies for local area networks (LANs) that is standardized as IEEE 802.3. An Ethernet protocol with 100Mbps data rates that named Fast Ethernet has been established to carry out the communication and data conversion between the target cluster and the host.

**ii) Shared Memory:** Shared memory provides a large space of random access memory (RAM) that can be accessed by several different CPUs in a multi-processor computer system. Multi-processors can independently operate but share the same memory resources. A shared memory scheme is easy to program since all processors share a single data and the communications between processors can be as fast as memory accesses to a same motherboard.

**iii) OpComm:** A complex SIMULINK model that implemented in RT-LAB must make some modifications so that the model can be separated as several subsystems and to be converted to fit the simulation environment. The useful communication blocks named OpComm that built in RT-LAB blockset of SIMULINK library is necessary and is inserted into each subsystem for effective connections and data acquisitions in real-time status.

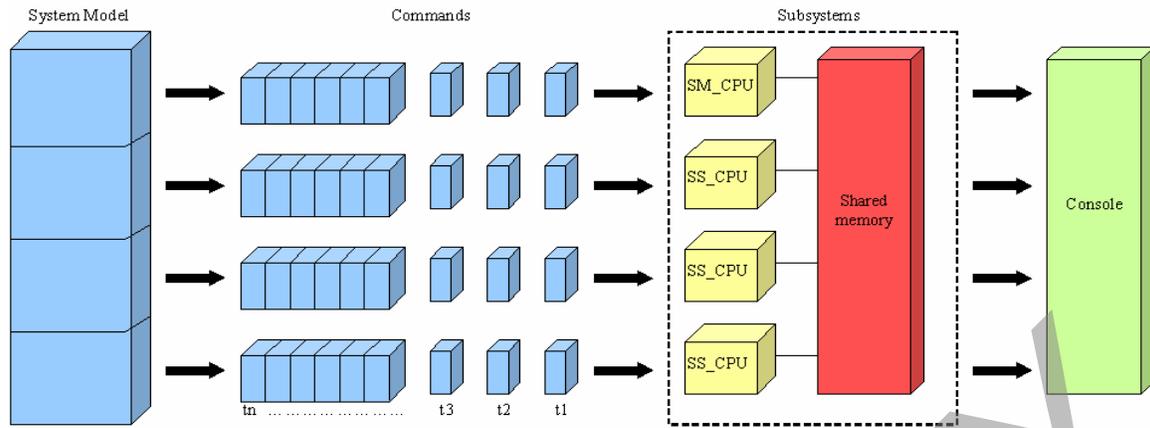


Fig. 3. Parallel separation of a complex system model.

### III. PARALLEL OPERATION AND SYNCHRONIZED MODE

Parallel computing is the simultaneous use of multiple computing resources to finish a computational task. An effort of parallel computing with a complex model is mainly dependent on the separation of that model into many subsystems and synchronized to run in parallel. A procedure of model separation in the study is shown in Fig. 3. For a more complicated system model (SIMULINK model) in host, the user can arbitrarily decompose the model into many discrete subsystems based on your own knowledge. Each subsystem is further broken down to a series of commands. Then the commands from each subsystem are executed simultaneously on the target cluster with different CPUs; meanwhile, only one subsystem is assigned as master subsystem (SM) and others are for slave subsystems (SS). Typically, if the system includes several nonlinear devices or logical computation units, it is better to break these components into a subsystem individually so that the computational burden can be more evenly distributed at each CPU and the simulation speed is accelerated.

The coordination of parallel tasks in real time is often associated with communications. In parallel computation, it often provides a synchronization point within an application where a task may not proceed until another task meets the same or logically equivalent point. Synchronization is usually required in real-time simulation that involves waiting by at least one task. Three types of synchronization modes are provided in RT-LAB, Free-run simulation, software synchronization, and hardware synchronization, where the free-run simulation mode is adopted in the study. In general, there is no synchronization done while the simulation is performed in the free-run mode. Thus target nodes in a distributed simulation are synchronized with the communication link (a designated real-time link or TCP/IP).

### IV. CASE STUDY

The steel plant including electric arc furnaces (EAFs) is a major electric pollution source and causes many power quality problems. Due to the extensively use of nonlinear loads, harmonics, flickers, and imbalances are commonly seen PQ problems associated with the power system including the electric arc furnace. Figure 4 shows an one-line

diagram of the studied steel plant power system, where the system consists of two electric loops: EAF loop and rolling mill (RM) loop. The EAF loop includes a 50-ton EAF load for steel making and the RM includes several motors (an AC 12-pulse motor, three DC 6-pulse motors, and a 6-pulse induction heater) to change the width or the thickness of the refined steel product. In [6] some field measurements of this system and the off-line simulation are reported. In order to improve the computational efficiency by performing off-line simulation, a real-time parallel simulation is implemented for the same system.

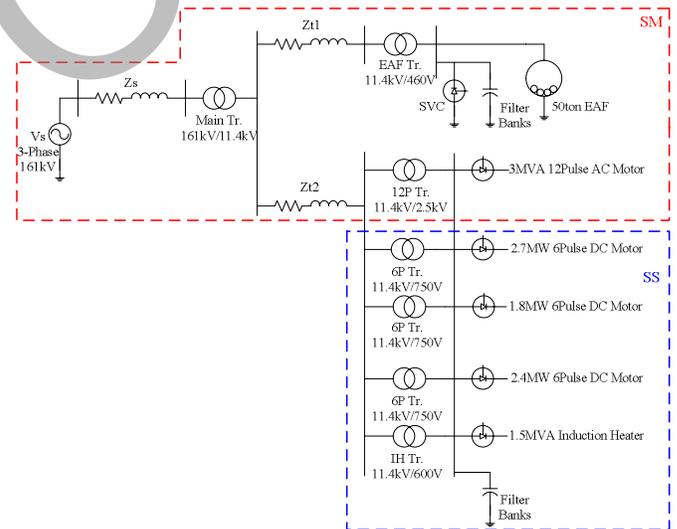


Fig. 4. One-line diagram of a steel plant power system.

Considering the power system shown in Fig. 4, the network can be broken into two subsystems in real-time parallel simulation. By assigning two subsystems with which one is SM including all components in EAF loop and an AC 12-pulse motor, and another one is SS including three DC 6-pulse motors and a 6-pulse induction heater. After the two subsystems are assigned to the target cluster, the real-time parallel simulation is performed. In the study Intel® Core™ 2 Quad 2.4 GHz CPU with a 1.0 GB memory COTS PC is used as the target cluster.

Base on the diagram of power system in Fig. 4 or the off-line simulation circuit in [6], a distributed real-time circuit of the steel plant power system that developed in

MATLAB/SIMULINK is shown in Fig. 5. Besides subsystems SM and SS, a subsystem console (SC) is also required for observing the outputs of the simulation results. The operation of SC do not performed in target cluster, it only receives and displays the output data to scope blocks by the communication link that connected with target cluster.

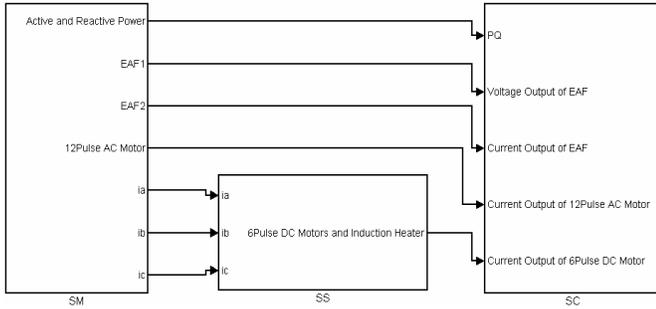


Fig. 5. A distributed real-time simulation in MATLAB/SIMULINK.

Figures 6-8 show results that obtained by the off-line and real-time simulations, where the dotted line indicates the off-line simulation and the solid fill line indicates the real-time simulation. In Figure 6 it gives the EAF active and reactive power consumption of the steel plant. In the study system, the measured EAF arc voltage is modeled as a harmonic voltage source to represent the behavior of an AC EAF. The voltage and current waveforms in the EAF transformer secondary side during refining stage are observed in Fig. 7. Simulation results of a 6-pulse dc motor and a 12-pulse ac motor are shown in Fig. 8, where the current waveform are rich in  $6p \pm 1$  and  $12p \pm 1$  ( $p = 1, 2, 3, \dots$ ) characteristic harmonic components. In Figs. 7 and 9, the phase difference of the two waveforms in each figure is mainly due to the initial solutions are different for solvers adopted in the off-line and the real-time simulations.

A solver setting and time efficiency for off-line and real-time simulation is listed in Table I. Due to the simulated system in the study includes many nonlinear loads, a great number of corresponding differential equations are therefore required for describing the system. The solver ode23tb is used for solving such “stiff” nonlinear differential equations in off-line simulation; furthermore, ode23tb is only provided in a variable-step and the step size is automatically chosen by the software. On the other hand, the step type of fixed-step is necessary for real-time simulation, where ode4, a solver based on the Runge-Kutta method, is adopted in the study with a 100  $\mu$ s step size. In addition, the advanced ARTEMIS algorithm, art3hd, is included to overcome some limitations of using ode4 solver alone with the fixed time step. The art3hd discretization method is a very stable method with good precision, especially in highly nonlinear networks, and it is the only integration method capable of simulating the model with a time step greater than 100  $\mu$ s. In the study a simulation time of 0.6 second is set to perform simulation for both off-line and real-time cases on the same PC platform. It is observed that the executed time of off-line simulation takes more than 90 minutes, in comparing with nearly 15 seconds of the real-time simulation at the same level of the solution accuracy.

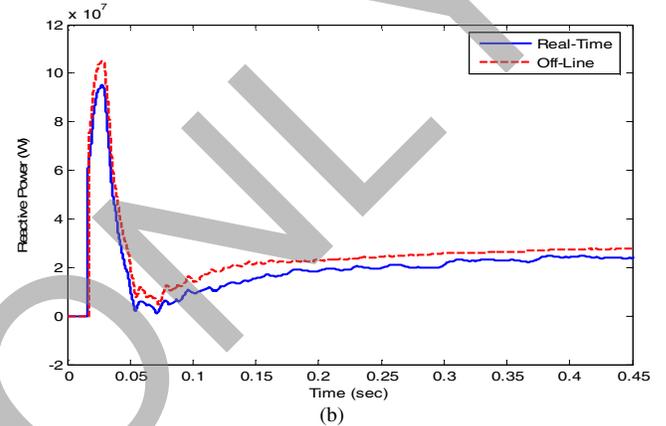
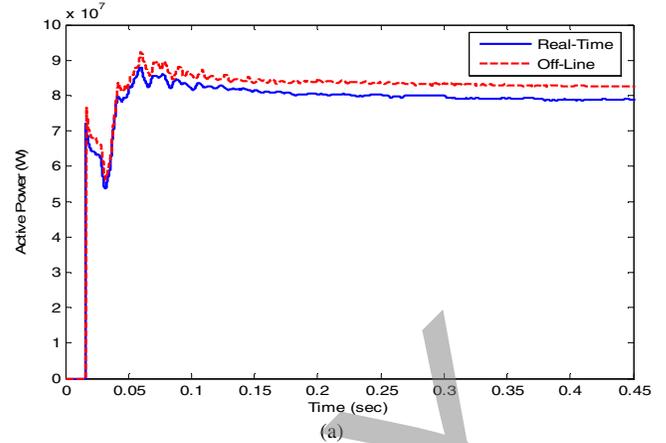


Fig. 6. (a) active power and (b) reactive power in off-line and real-time simulations

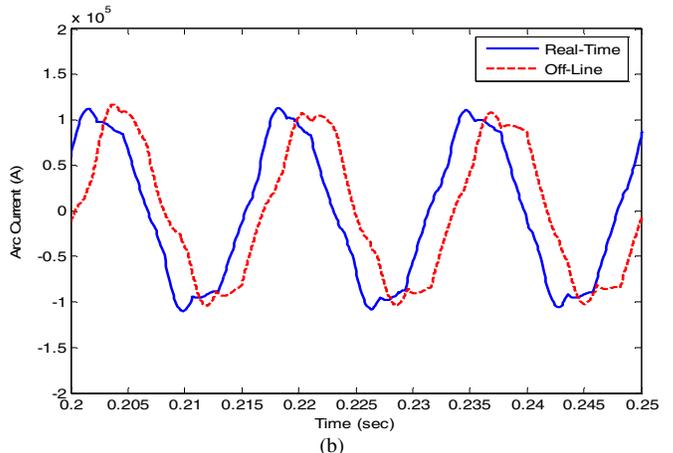
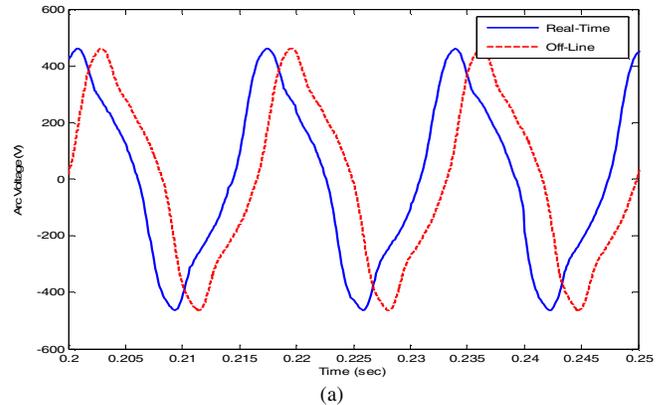


Fig. 7. (a) arc voltage and (b) arc current in off-line and real-time simulations

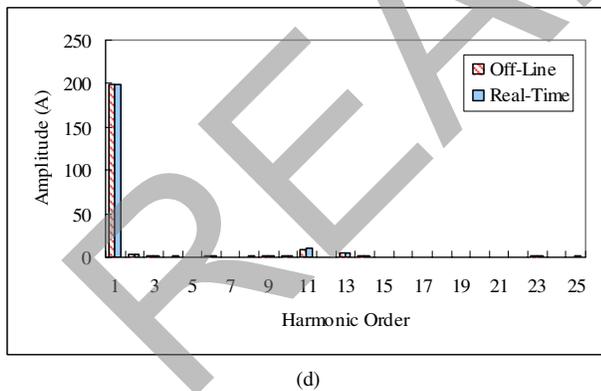
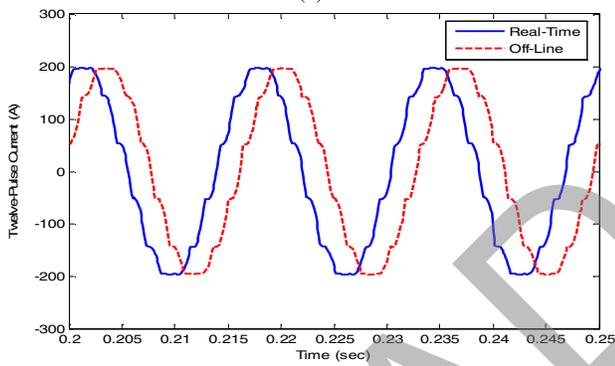
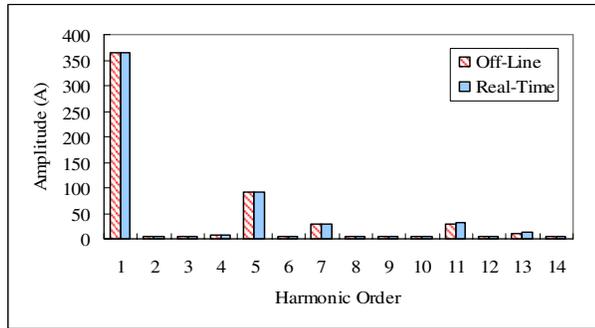
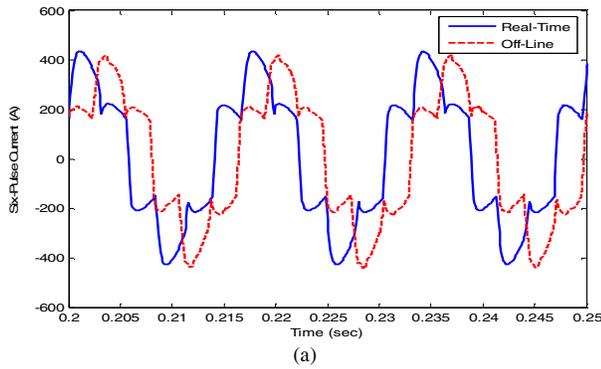


Fig. 8. (a) current waveforms of 6-pulse dc motor, (b) frequency spectra of (a), (c) current waveforms of 12-pulse ac motor, and (d) frequency spectra of (c) obtained by the off-line and real-time simulations.

## V. CONCLUSIONS

This paper presents an application of real-time simulation technique for harmonics study of an industrial power system including EAF and other nonlinear loads. The study system network model under test is decomposed into two subsystems for implementing a distributed simulation. Results show that

the real-time simulation gives a computationally efficient performance than conventional off-line simulation, while the accuracy of the solution is maintained. It is concluded that an effective real-time distributed simulation has a good potential for more complicated power quality studies.

Table I  
Solver Setting and Time Evaluation

Simulation Types	Off-Line	Real-Time
Solver	ode23tb (stiff/TR-BDF2)	ode4 (Runge-Kutta) with art3hd ARTEMIS algorithm
Step Type	Variable-Step	Fixed-Step
Step Size	Auto	100 us
Simulation Time	0.6 sec	Free-run but assigned to stop at 0.6 sec
Executed Time	1 hr 34 min 19 sec	14.578 sec

## VI. REFERENCES

- [1] L. F. Pak, M. O. Faruque, X. Nie, and V. Dinavahi, "A versatile cluster-based real-time digital simulator for power engineering research," *IEEE Trans. on Power Systems*, Vol. 21 No. 2, May 2006, pp. 455-465.
- [2] C. Dufour and J. Belanger, "Real-time PC-based simulator of electric systems and drives," in *Proc. Int. Conf. on Parallel Computing Electrical Engineering*, Vol. 1, Sep. 2004, pp. 105-113.
- [3] Opal-RT Technologies Inc., ARTEMIS Version 4.1, User's Guide.
- [4] Opal-RT Technologies Inc., RT-LAB Version 8.1, User's Guide.
- [5] ONX Software Systems., QNX Neutron RTOS Version 6.3, User's Guide.
- [6] G. W. Chang, Y. J. Liu, H. M. Huang, and S. Y. Chu, "Harmonic analysis of the industrial power system with an AC electric arc furnace," in *Proc. IEEE PES General Meeting*, June 2006.

## VII. BIOGRAPHIES

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