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CARBON REDUCTION POTENTIAL WITH INTELLIGENT CONTROL OF POWER SYSTEMS

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Abstract: Climate change caused by anthropogenic greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) is now widely accepted as a real condition that has potentially serious consequences for human society and industries need to factor this into their strategic plans. One salient planning assumption is that energy - essential for every activity - will become more expensive relative to other inputs. Economic growth does not have to be linked to an increase of GHG emissions and can be attained in addition to the usage of renewable energy sources by using energy efficiency technologies for power system generation, transmission, and distribution. The development of intelligent energy-efficient control technologies will both soften negative effects of the climate change on the economy and enhance energy security.

This paper outlines the significant carbon reduction potential with intelligent control and optimization techniques applied to power system generation and transmission systems with and without wind farms. *Copyright © 2008 IFAC*

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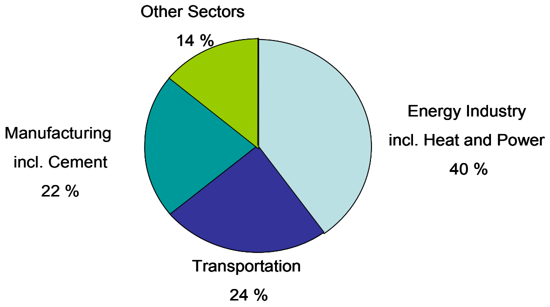
1. INTRODUCTION

Climate change is the largest element of environmental change, as it covers the globe and extends to time horizons beyond the lifetimes of the people alive today. In the middle of the twentieth century long-term accumulation of greenhouse gases such as carbon dioxide (CO_2) has become evident (Labatt and White, 2002). It has also become evident that, after a transition period of fluctuating temperatures between 1945 and 1975, the earth is heating up steadily (Environment Canada, 1988).

The understanding of anthropogenic influences on climate has improved and has lead to a very high confidence that rising concentrations of CO_2 and other greenhouse gases (GHGs) in the atmosphere were caused by human activities and cause global temperatures to rise, with accompanying climate changes (Grubb *et al.*, 1999; Intergovernmental Panel on Climate Change (IPCC), 2007).

The potentially serious consequences of climate change are not only of scientific concern. It is expected that climate change will have an enormous impact on the world economic as well. The estimated costs of an unabated climate change are as much as 20% of the global domestic product (GDP). However, by taking the appropriate measurements these costs could be limited to around 1% of GDP (Stern, 2006). Hence, there is a growing belief that, although adaptation to climate change and acceptance of necessity to reduce GHG emissions will entail costs, these costs are regarded to be likely to be more bearable than the potential costs to procrastination and companies that are not preparing for climate change might lose their competitive edge (Labatt and White, 2007). It has been accepted that CO_2 emissions are going to be regarded as a liability and the ability to reduce CO_2 emissions will soon become an important asset in a carbon-constrained world.

The power and energy industry - in terms of economic importance and environmental impact – is one of the most important sectors in the world since nearly every aspect of industrial productivity and daily life are dependent on electricity. At the same time the power and energy industry represents a major portion of global CO_2 emission, which is responsible for 40% of the global CO_2 production (see Fig. 1). It is followed by the transportation sector, which covers 24%, the manufacturing sector (including cement) with 22%, and other sectors covering the rest (Labatt and White, 2007).



Source: Based on data from World Business Council for Sustainable Development (WBCSD), 2005: The Cement Sustainability Progress Report, WBCSD, Geneva, www.wbcsd.org.

Fig. 1. Global CO_2 Production.

With 20 tons per capita the U.S. has the highest CO_2 emissions per capita in the world (Labatt and White, 2007, with further references) and U.S. based power utilities generate power on a lower efficiency level than power utilities in the European Union (EU) and Japan (PricewaterhouseCoopers (PwC) and Enterprise, 2003; *idem*, 2002).

Energy efficiency has been on the agenda of power utilities and climate change concerns are bringing new urgency and priority to energy efficiency initiatives (PwC, 2007) since improving energy efficiency is the fastest, the most suitable, and the cheapest way to reduce GHG emissions and to enhance energy security (G8 Summit, 2007).

In the U.S., at least five carbon-emission bills and the so-called 2007 Energy Efficiency Promotion Act (S. 1115) have been introduced to the Congress, supposed to give legislative backing to efficiency standards and targets that have the goal of saving substantial amounts of power and GHG emissions.

A variety of responses are required to countersteer climate change (Labatt and White, 2007). Investments in renewable energy sources cannot stand alone because renewables are not (yet) able to provide the massive load power that result from conventional energy sources (Romm, 1999). They will need to be supplemented by efficiency-improvements of conventional energy sources as well as power system transmission and distribution technologies, and measurements to stimulate the development of low-carbon technologies. The global potential for saving energy through energy efficiency measurements is huge. According to the International Energy Agency (IEA) successfully implemented energy efficiency measurements could contribute to 80% of avoided GHGs while substantially increasing security of supply (G8 Summit, 2007).

The rest of this paper is organized as follows: Section 2 presents the power grid technologies to minimize real power losses, fuel cost and emissions through reactive power and voltage control, optimal power flow and optimal combined economic and emission dispatch. Section 3 describes the popular Computational Intelligence (CI) paradigms applicable for control and optimization to the problem of interest in this paper. Section 4 presents some case studies and results on the application of CI paradigms for solving power system problems that promises carbon reduction. Finally, the conclusion and the future work are given in Section 5.

2. GRID TECHNOLOGIES

The typical electric power grid is a geographically large interconnected network consisting of generators, transmission lines, real and reactive power compensators, loads and alike. The high voltage transmission system links the generators to substations, which supply power to the user through the distribution systems. The general configuration of a modern power system is that power sources and loads are widely dispersed. The number of bulk power exchanges over long distances has increased as a consequence of the deregulation of the electric power industry, the growing demand for electricity and dependence of critical infrastructures on the supply of electricity. The stability, security, and sustainability of the power system are of high importance today.

Usually, distributed control agents are employed to provide reactive control at several places on the power network through power system stabilizers (PSSs), automatic voltage regulators (AVRs), Flexible AC Transmission Systems (FACTS) devices, etc. These devices play a decisive role in the energy-efficiency improvement since they are able to improve both system efficiency and reliability (Labatt and White, 2007), allowing alternative sources of energy (windfarms, solar, and fuel cells) to be integrated to the grid. The optimal settings of these devices for optimal reactive power and voltage control are always challenging to determine. Appropriate reactive power and voltage control can minimize system losses at all time.

System-wide disturbances in power systems are a challenging problem for the utility industry. Further, because of new constraints placed by economical and environmental factors, the trend in power system planning and operation is toward maximum utilization of existing electricity infrastructure, with tight operating margins, and increased penetration of renewable energy sources such as wind power. Under these conditions, power systems become more complex to operate and to control, and, thus, more vulnerable to a disturbance (Begovic *et al.*, 2005). When a major disturbance occurs, advanced protection and intelligent control actions are required to stop the power system degradation, restore the system to a normal state, and minimize the impact of the disturbance.

Economic load dispatch is one of the important functions of energy management systems where the optimal real power settings of power plants are determined with the primary objective of minimizing total fuel cost (Trefny and Lee, 1981). Generation of power from fossil fuels emits GHGs such as sulphur dioxides, nitrous oxides and CO_2. Therefore, utilities are under pressure today to factor emissions in solving the power dispatch problem (Lamount and Obesis, 1995). The Combined Economic Emission dispatch (CEED) problem is a complex constrained optimization problem with many local optima. A number of classical optimization techniques are challenged by the nature of this problem and get trapped in a local minimum. In addition, the computational overhead is enormous as the search space grows with increasing number of power generation units.

3. INTELLIGENT CONTROL AND OPTIMIZATION TECHNIQUES

Several paradigms of CI exist today but the main ones include those shown in Fig. 2 and their combinations (Venayagamoorthy, 2005). Among the different paradigms of CI, neural networks have the closest resemblance to the human brain functioning and likewise the artificial immune networks to the biological immune system. Neural networks are capable of approximating nonlinear functions which has the potential to be widely utilized for prediction and control of complex systems. The artificial immune networks are capable of identifying non-self properties and counteract them. They are useful computational tools for regulatory controls. Fuzzy logic allows approximate reasoning and these are suitable tools for modeling commonsense. New facts with a degree of certainty can be inferred from uncertain facts. Swarm intelligence allows for coherent global patterns to emerge from the collective interaction of simple agents with the environment. Evolutionary computing models the natural evolution where adaptation takes place to improve the survival capabilities through natural selection, survival of the fittest, reproduction, mutation or symbiosis.

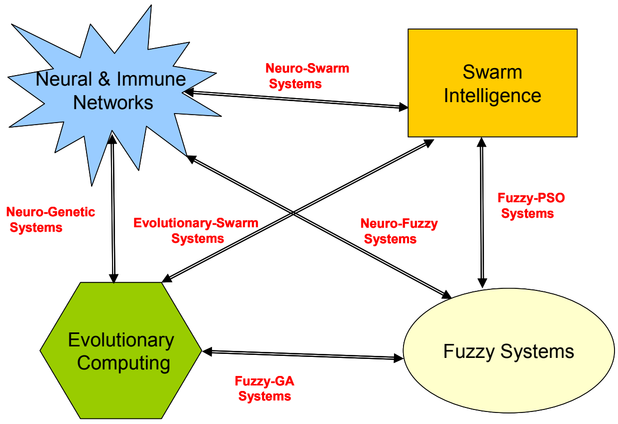


Fig. 2. Paradigms of computational intelligence.

Advanced CI techniques based on hybrids of the individual CI paradigms provide robust solutions that no single one can provide by itself. Neural networks trained by Particle Swarm Optimization (PSO) provide better nonlinear approximations (del Valle, 2005).

Different intelligent agents based on these CI paradigms have shown promising results for various fields of applications including control and optimization of nonlinear systems such as the electric power systems (del Valle *et al.*, 2007; Venayagamoorthy and Harley, 2005). Neural network based adaptive and optimal control are able to provide appropriate control as system operating points and conditions change over time. Optimal parameters of power system controllers found over a wide range of operating points and conditions using PSO algorithms provide the best controller performance (Das and Venayagamoorthy, 2006).

4. APPLICATIONS OF INTELLIGENT TECHNIQUES – CASE STUDIES

The authors resent three case studies with promises for carbon reduction with CI techniques taken from the first author work and others The authors present three case studies with promises for carbon reduction with CI techniques taken from the first author's work and others in the literature where CI techniques are used to improve the stability, security, and sustainability of power systems.

4.1 Reactive and Voltage Control

Due to the steady increase in the complexity of power systems and the continuous high loading of network components, abnormal operating conditions such as under voltage may occur more frequently. Hence, the need for appropriate reactive power and voltage control of the power system is evident. The reactive power dispatch has two-fold objectives thus: to improve the system voltage profile and to minimize system losses at all times. The reactive power can be varied by suitably controlling a number of devices on the power system including: generating units excitation, switched capacitors and reactors, FACTS devices, switching transmission lines, transformers equipped with tap changers.

The aforementioned control devices have lower and upper permissible limits and are distributed system-wide. It is therefore evident that the reactive power and voltage control problem for a large power system is very complex encompassing different control devices, some of which being continuously adjustable whilst others being of discrete steps that are numerous, asymmetrical and located geographically dispersed. The existence of multiple optimum solutions is inevitable, especially when there are many control devices to be adjusted to obtain desired system voltages in a typically large power system. Thus, there is a need for CI techniques to achieve the global optimum solution of the reactive power dispatch problem. Particle swarm optimization and differential evolution (DE) have been proposed to solve this problem and compared in Bakare *et al*, 2007. The problem is formulated as a minimization of power losses subjected to equality and inequality constraints and results are presented for two systems - the Nigerian Power System and New-England power system.

For the study on the Nigerian power system, it has been demonstrated that PSO and DE algorithms are able to bring about 16.62% and 13.55% reduction in the power losses for a case where the initial settings of transformer taps were wrong and two 75 MVar reactors wrongly switched on. The restored voltage profiles with PSO and DE are shown in Fig. 3 below. Other case studies under different operating conditions have also resulted in power loss reduction (Bakare *et al*, 2007). Minimization of power losses translates to carbon reduction.

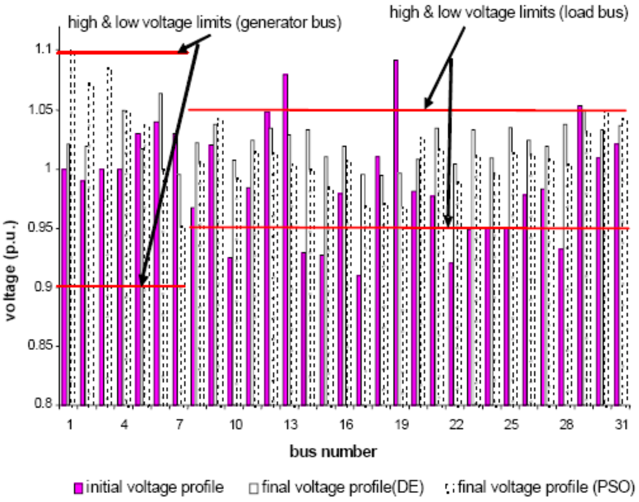


Fig. 3. Initial and final voltage profiles (before and after optimization with DE and PSO).

4.2 *Wide Area Coordinated Control of Wind Farms and FACTS Devices*

To improve the system-wide dynamic performance and stability, wide-area coordinating control (WACC) is becoming an important issue in the power industry. A WACC operates at a global level, e.g., the control center of a power system to coordinate the actions of local controllers. Due to the large-scale, nonlinear, stochastic, and complex nature of power systems, traditional mathematical tools and control techniques are not sufficient to design such a WACC. This problem can be overcome by using neural networks (NNs) and adaptive-critic-designs (ACDs) based intelligent nonlinear optimal control techniques (Werbos, 1992; Prokhorov *et al.*, 1997).

During the past years, ACD-based optimal neurocontrol has been proposed to improve power system dynamic and transient performance (Venayagamoorthy *et al.*, 2003; Park *et al.*, 2004). However, these previous works focused on the local control of individual power system devices. In Qiao *et al.*, 2007, an optimal wide-area coordinating neurocontroller (WACNC) for a power system with power system stabilizers, a large wind farm, and FACTS devices is studied using an advanced adaptive critic design approach - the Dual Heuristic Programming approach. The power system on which the WACC is implemented is shown in Fig. 4. Area 1 is predominantly a generation area with most of its generation is from hydro plants (G1 and G2). Area 2, located between the main generation area (Area 1) and the main load center (Area 3), has a large wind farm (G4), but it is insufficient to meet local demand. Area 3, situated about 500 km from Area 1, is a load center with some thermal plants (G3). Further, since the generation units in Areas 2 and 3 have limited energy available, the system demand must often be satisfied through transmission. The transmission system consists of 230 kV transmission lines except for one 345 kV link (line 7-8) between Areas 1 and 3.

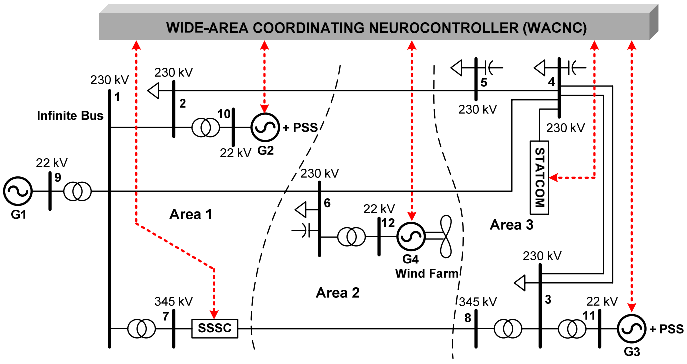


Fig. 4. 12-bus power system with a large wind farm (G4), a STATCOM and an SSSC coordinated by an optimal WACNC.

The STATCOM is a shunt connected FACTS device and is placed at bus 4 in the load area (Area 3), for steady state and transient voltage support. This relieves the under-voltage problems in Area 3 (Jiang *et al.,* 2006). The SSSC is a series FACTS device and is placed at the bus 7, end of line 7-8, to regulate its power flow. This arrangement can relieve the possible transmission congestion on line 1-6 caused by some contingencies in Area 3 (Jiang *et al*., 2006; Qiao *et al*., 2006). The local controllers on this power system are each designed at the conventional linear control techniques and local signals, but are coordinated by the WACNC to achieve the desired system-wide performance goals. The design details of the WACNC are explained in Qiao *et al*., 2007.

A three phase short fault is applied to the system in Fig. 4 at bus 3 and the fault is cleared by tripping one of the parallel lines after 150 ms. This makes the system topology different and the local controllers are not able to damp the power system oscillations (see Fig. 5). But with the WACNC the oscillations are damped and the operation of the wind farms continues with no disruption. In this study, even with delays (*d*) up to 160 ms in the communication of the remote signals to WACNC site, the performance of the WACNC is not degraded. Robust controllers are essential to ensure the stability of the power system. Otherwise, the wind farms will be tripped and this means intake power from other power plants with non-zero carbon emissions.

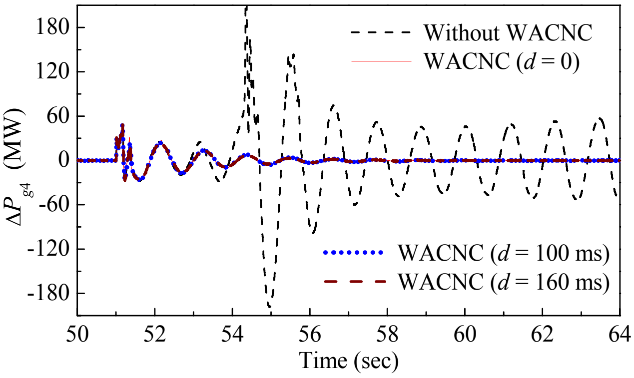


Fig. 5. Variation in the output of wind farm during a three/phase short circuit at bus 3 and the tripping of one of the parallel transmission lines with and without WACNC.

4.3 *Combined Economic and Emission Dispatch Problem*

Economic load dispatch (ELD), used as part of the modern energy management system, is aimed at minimizing the total generation fuel cost of thermal plants while satisfying certain system constraints (Bakare *et al.,* 2005). However, ELD alone is not sufficient to reduce the pollutant emissions caused by fossil fuel burning for power generation. Thus, it becomes necessary to implement economic emission dispatch (EED) model, which aims at minimizing both generation fuel cost and emissions simultaneously. Whenever minimum cost of operation is taken as sole optimization objective, the corresponding emission level increases. Similarly, when minimum emission dispatch is taken as the sole objective, it results in higher operating cost. Therefore, both objectives are conflicting in nature and some weights must be assigned to obtain a non-inferior solution. This requires algorithms that can solve effectively multiple conflicting objectives under a number of constraints. Under such cases, the aim is to determine the trade-off surface, which is a set of non-dominated solution points, known as the Pareto optimal solutions. Every point on the Pareto front is an acceptable solution.

CEED problem has been studied by several researchers as a multi-objective problem using computational intelligence techniques such as non-dominated sorting genetic algorithm (NSGA-II) (Ah King and Rughooputh, 2003) and evolutionary programming (Jeyakumar *et al.*, 2007). The problem is formulated as a nonlinear constrained multi-objective problem in the latter study as follows:

$$\begin{aligned} &Min \quad f=[F_1,F_2] \\ &subject\ to\ g(P_{Gj})=0 \\ &\qquad\qquad h(P_{Gj})\le 0 \end{aligned} \tag{1}$$

where:

F_1 is the total fuel cost of generation formulated as:

$$F_1=F(P_{Gj})=\sum_{j=1}^{N}a_jP_{Gj}^2+b_jP_{Gj}+c_j \quad \$/hr \tag{2}$$

N is the number of generators, a_j, b_j and c_j are the cost coefficient of generator j and P_{Gj} is the power generated by the j^{th} unit.

F_2 is the total emission of pollutants of the N generating units, expressed as a quadratic polynomial below:

$$F_2=E(P_{Gj})=\sum_{j=1}^{N}d_jP_{Gj}^2+e_jP_{Gj}+f_j \quad Kg/hr \tag{3}$$

d_j, e_j and f_j are the emission coefficients of generator j. The emission curve is directly related to the cost curve by the emission rate per MBtu. This is usually a constant value for a given type of fuel.

g and h are the problem equality and inequality constraints.

The details on this implementation using the multi-objective evolutionary programming (MOEP) is given in (Jeyakumar *et al.*, 2007). The MOEP has been applied to a three-unit and a six-unit test system. The results obtained were compared with that obtained using the NSGA-II and weighted sum methods. MOEP results in a very good Pareto front in a single run and is shown on the same computing platform to be about five times faster than the weighted sum approach. The faster the algorithm can be for solving this CEED problem, the potential for dynamic optimization and further CO_2 reduction.

5. CONCLUSION

There is a growing acceptance in the business community that global climate change is a real phenomenon that requires immediate response to avoid serious consequences for human society. The response will be a significant reduction, sequestration, or elimination of GHG emissions to offset potential global climate change. Such response will need to include an improvement of energy-efficiency of conventional energy sources.

CI techniques provide the benefits of robust and optimal solutions for control and optimization of power system operations, with reduced computational overhead. The optimal combination for switching of reactive power compensation devices for minimal power losses can be achieved with CI paradigms. Advanced neural networks based techniques can be used to enhance the stability of power systems with wind farms thus ensuring that zero emissions are maximized. Of course, renewable energies cannot supply the total load demand requiring the supply from conventional power plants. With CI paradigms, the nonlinear multi-objective constrained combined economic emission dispatch problem can be solved optimally and faster.

The future relies on taking these CI paradigms to solve the control and optimization issues for power system operation dynamically and optimally. The authors believe adaptive critic designs have the potential to address this in a way, which could be an optimal combination between effective climate protection and energy security. The exact way remains to be investigated.

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