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Real-Time Adaptive Optimization Engine Algorithm for Integrated Volt/VAr Optimization and Conservation Voltage Reduction of Smart Microgrids

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SUMMARY

In recent decade, smart microgrids have raised the feasibility and affordability of adaptive and real-time Volt/VAr optimization (VVO) and Conservation Voltage Reduction (CVR) implementations by their exclusive features such as using smart metering technologies and various types of dispersed generations. Smart distribution networks are presently capable of achieving higher degrees of efficiency and reliability through employing a new integrated Volt/VAr optimization system. For VVO application, two well-known approaches are recommended by different utilities and/or companies: Centralized VVO and Decentralized VVO. In centralized VVO, the processing system is placed in a central controller unit such as DMS in the so called "Utility Back Office". The DMS uses relevant measurements taken from termination points (i.e. utility subscribers) supplied to it from either field collectors or directly from MDMS, to determine the best possible settings for field-bound VVO/CVR assets to achieve the desired optimization and conservation targets. These settings are then off-loaded to such assets through existing downstream pipes, such as SCADA network In contrast, decentralized VVO utilizes VVO/CVR engines which are located in the field and in close-proximity to the relevant assets to conserve voltage and energy according to local attributes of the distribution network. In this case, local measurements do not need to travel from the field to the back-office, and the new settings for VVO/CVR assets are determined locally, rather than from a centralized controller.

Without having any preference between abovementioned VVO techniques, this paper studies an adaptive optimization engine for real-time VVO/CVR in smart microgrids based on Intelligent Agent technology. The optimization algorithm provides the best optimal solution for VVO/CVR problem at each real-time stage through minimizing system loss cost and improves system energy efficiency as well as voltage profile of the relevant distribution system. The algorithm may employ distributed generation sources to address the Volt/VAr optimization problem in real-time.

Coordinated VVO/CVR requires real-time data analysis every 15 minutes. It utilizes a distributed command and control architecture to supply the VVO Engine (VVOE) with the required data, and secures real-time configuration from the VVO engine for the VVO control devices such as On-Load Tap Changers (OLTCs), Voltage Regulators (VRs) and Capacitor Banks (CBs). It also has the option of employing distributed generation (DG) as well as modelling load effects in VVO/CVR application.

The algorithm minimizes the distribution network power loss cost at each time stage, checks the voltage deviation of distribution buses and distributed generation sources considering different types of constraints such as system power flow, distribution network power factor, system active and reactive power constraints and switching limitations of Volt/VAr control devices. The algorithm

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receives required real-time data from an intelligent agent. Then, it starts to solve the real-time VVO/CVR problem in order to find the best optimal configuration of the network in real-time.

The paper uses British Columbia Institute of Technology (BCIT) distribution network as its case study in order to explore the effectiveness and the accuracy of the optimization engine. Moreover, the VVO/CVR optimization algorithm is implemented in different configurations; a) VVO/CVR confined to the substation and b) VVO/CVR optimization algorithm within the substation and along distribution feeders. The algorithm also checks the availability of DGs to assist VVO/CVR control functions and assesses the impact of new distributed sources such as: Flywheel Energy Storage System (FESS) on real-time VVO/CVR. For this reason, the algorithm classified DGs in a microgrid based on their impacts and instantiates them based on their application feasibility for real-time VVO/CVR.

KEYWORDS

Volt/VAr Optimization, Conservation Voltage Reduction, Smartgrid, Distribution Network, Distributed Generation, Loss Reduction

1. Introduction

Nowadays, the advent and the expansion of Smart Grids have led to new opportunities and considerations in power systems, especially in electrical distribution networks. Various types of advanced distributed energy sources, new operational and management systems such as: Distributed Management Systems (DMS), Advanced Metering Infrastructure (AMI), Substation Automation and Energy management systems (EMS) are some of the functionalities electric utilities are exploring in order to make their distribution systems more efficient and smart.

The inherent characteristics of smart microgrids have permitted new end-users such as Plug in Hybrid Electric Vehicle (PHEVs) users, energy storage systems and residential customers with co-generating units to grow in new distribution networks. Thus, electrification of wide variety of unpredictable loads with different levels of impacts on quality and reliability of the system has exposed the importance of Quality of Services (QoS) in existing distribution systems. In the transition path to a smarter and more secure distribution network, the key factors are energy efficiency and power loss reduction. Hence, utility companies have put lots of efforts on “smartening up” their systems based on optimal energy efficiency programs and reliable power loss reduction techniques.

Volt/VAr Optimization (VVO) is one of the well-known techniques traditionally employed to reduce power losses in distribution feeders. VVO is an advanced decision making method that can optimize voltage and/or reactive power (VAr) of a distribution network in an efficient way conforming to predetermined aggregated feeder load profiles. This can be performed through operating transformer load tap-changers (OLTCs), Voltage Regulators (VRs), Capacitor Banks (CBs) and other existing Volt/VAr control devices in distribution substations and/or along distribution feeders.

The other method that may prove beneficial to both utilities and distribution consumers is Conservation Voltage Regulation or Conservation Voltage Reduction (CVR). CVR attempts to maintain customer’s voltage level in the lower limit of ANSI or CSA standard acceptable range [1], [2] in order to effect energy conservation without imposing any changes in customer’s behavior.

Mostly, conventional Volt/VAr control techniques have confined to a static voltage control at the substation and medium-voltage level. Thus, bringing a real-time dynamic Volt/VAR optimization from substation to the edge of the feeders has always been a complicated issue to implement. Nowadays, it is more conceivable to evolve the conventional static VVO and CVR systems into real-time, adaptive and dynamic VVO/CVR solutions via smart microgrids real-time command and control capabilities.

The availability of Smart Metering technologies and their capabilities in transmitting massive amounts of data can make VVO and/or CVR more accurate and flexible. Furthermore, VVO/CVR strategies can be more affordable and practical with the existence of dispatch-able energy sources such as Vehicle to Grid (V2G) systems, Energy storage and smart inverter technologies. In addition, new Intelligent-based approaches such as Multi Agent Systems [27] in smart microgrid networks can certainly help implementing the required command and control solutions for such functions.

In recent years, great efforts have been spent in designing and developing efficient VVO or CVR solution for distribution networks in both academic and industrial settings [3]-[28]. The common view of most academic and industrial research studies is to segregate VVO and CVR [3]-[28]. Studies have been done on various modelling approaches (Fuzzy Logic and Mixed Integer Linear Programming (MILP) [3]-[8]), different heuristic optimization techniques (Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO) and hybrid techniques [3], [10], [17], [27]) as well as other optimization techniques (Bender's Decomposition), DSP-Based (Digital Signal Processing), Pseudo-measurements [6], [26], [28]). On the other hand, studies on new VVO optimizations approaches are being pursued by some Canadian utilities such as BC Hydro [16] and Hydro-Quebec [17], [25]. Different utilities such as BC Hydro [16], Hydro-Quebec [26], Hydro Ottawa [28] and Ontario LDC [28] have installed CVR systems at their substations since 2002. Moreover, most of the research works have studied centralized VVO [3]-[7], [10], [12]-[14], [29]-[30], [32]. There are not many studies that assess decentralized approaches for VVO. TABLE I presents comprehensive literature review of VVO/CVR research studies. Considering academic and industrial studies, future investigations are focusing on finding the optimal approaches based on the advantages of new Smart Grid-based technologies. Along this path, huge gaps exist between offline VVO and Smart Grid-based real-time VVO and CVR.

TABLE I VVO/CVR LITERATURE REVIEW OF PREVIOUS STUDIES

Specifications	References	This Paper
VVO/CVR	VVO [3-7, 10, 12-14, 30, 32], CVR [25, 26], Voltage Regulation [8, 11, 17, 27, 31, 33], VVO/CVR [9, 15, 16, 28, 29, 34]	Both VVO/CVR
Objective Function	Min. Loss [5-7, 29-30, 32, 34], Min. Energy Loss [10, 30], Min. Voltage Deviation [4, 8, 17], Improving Voltage Profile [31], others: Max. DG active power [11], Max. fuzzy membership values [3]	Min. Energy loss, Imp. Voltage Profile
Optimization Technique	Multi-objective Fuzzy [3, 5], Fuzzy [4, 8, 33], PSO [7, 10, 32-33], GA [30], SE [31], Bi-level optimization [11], Branch & Bound [29], Time-series [28], Benders Decomposition [6]	Heuristic: Improved Genetic Algorithm
Innovation in algorithm	Using Intelligent systems [8, 17], Bi-section search Algorithm [11], with open DSS [29], others [4, 6, 10, 33]	Distributed Command and Control, IA, DG based
Smartgrid adaptive	Conventional DG [10-12, 15-17, 32, 33]	Yes (DGs in smart microgrids)
Real-time	[8, 17, 31, 34]	Yes (15 minutes)
Explanatory/Interpretive papers	[12-15, 16, 25-26, 28]	Yes

Notwithstanding the considerable efforts of previous Volt/VAr optimization research projects and without considering any preference for either of centralized and decentralized VVO approaches, this paper studies the feasibility and sustainability of a real-time Smart Grid-based Volt-VAr/CVR optimization engine, that can control VVO/CVR in an integrated way through employing a comprehensive concept called "Intelligent Agent" system. The algorithm will enable distribution network operators to achieve higher degree of loss reduction, energy efficiency, voltage conservation and reliability simultaneously.

The main advantages of presented optimization algorithm include, but not limited to; Real-time coordination of VVO and CVR based on real-time data analysis, integration of VVO/CVR system with intelligent agent command & control architecture, coordinated control of VVO devices such as: OLTCs, VRs and CBs inside distribution substation and along distribution feeder, integrated control of distribution network feeders and ability to consider distributed generations and load effects on VVO/CVR.

Fig. 1, Illustrates the main structure of proposed approach for VVO/CVR for a feeder. As it is typically shown, a substation feeds a distribution feeder. Inside the substation and along distribution feeder, Volt/VAr control devices and distributed generation units are located. The distribution network feeds some customers at LV side. Each customer has a smart meter which can be connected to a Master Controller Unit (MCU) which sends smart meter data to the system Intelligent Agent (IA-IED). This Intelligent Agent is responsible for smart meters' data capture and data filtering. It sends the required data of VVO/CVR Engine in real-time. Then, the VVO/CVR Engine solves the optimization problem based on VVO/CVR objectives, constraints and data which has been sent by IA. The optimal solution will be sent back to the Volt/VAr control devices (they can also be IAs) to reconfigure distribution feeder in real-time. The algorithm is designed to implement VVO/CVR in related configurations.

First, it confines VVO/CVR to the substation and existing control devices. Then, if the optimization objectives are not satisfied, it will determine VVO/CVR control device candidates within the substation and along the feeder. In addition, the algorithm considers the role of distributed generations on voltage profile improvement and VAr injections. It checks the availability of DGs in microgrid in order to assist VVO/CVR according to DG priorities. The priorities are defined based on the effectiveness level of a DG in VVO/CVR application. As mentioned, the proposed algorithm is compatible with distributed command and control structure of smartgrids. In future smart distribution networks, each node is intelligent and will be able to control its system locally as a pre-emptive self-healing system. Hence, the adaptability of the VVO algorithm with future distributed control designs seems essential.

The paper has studied British Columbia Institute of Technology (BCIT) distribution network as an applicable case study by employing an adaptive heuristic search engine based on the evolutionary concepts (GA) and Intelligent Agent systems. The paper is organized in four sections. Section 1, primarily defines the problem and then, presents a comprehensive literature review. The second section, gives the basic structure and fundamentals of the proposed Smart Grid-based VVO/CVR algorithm. Section 3 focuses on the algorithm specifications, formulations and its other features. Section 4 gives case study information and assesses the results. Then, it explains system reconfigurations according to proposed real time-based VVO/CVR algorithm.

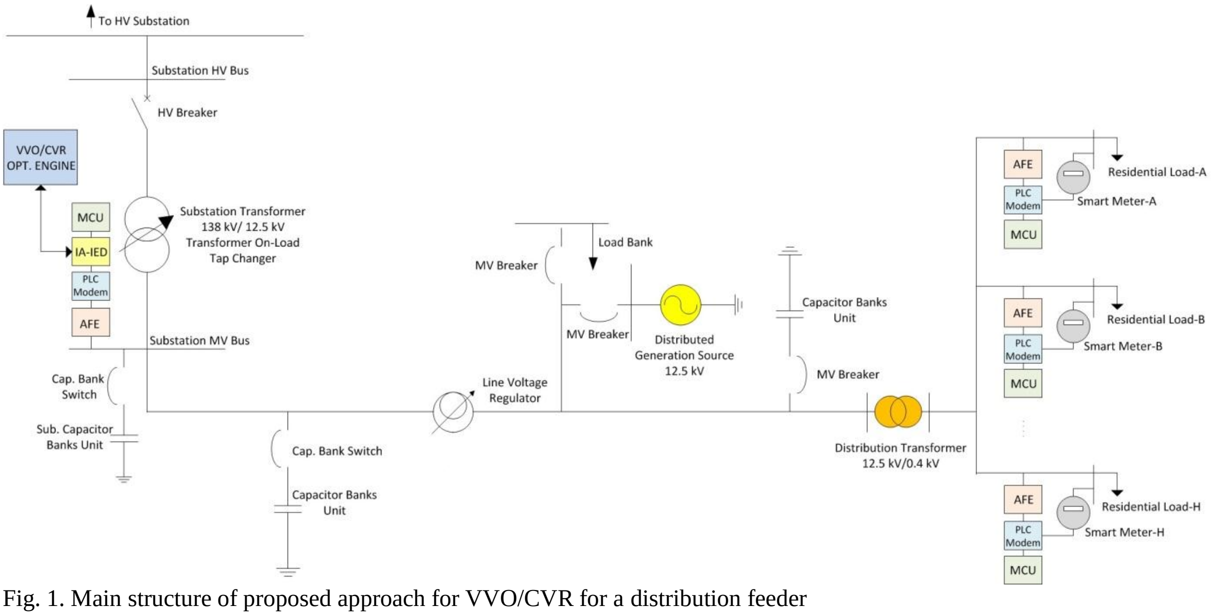

Fig. 1. Main structure of proposed approach for VVO/CVR for a distribution feeder

2. Structure and Fundamentals of Proposed Smart Grid-based VVO/CVR Algorithm

In this section, the main structure of VVO/CVR Engine is discussed and the optimization algorithm is explained in detail. As mentioned, VVO/CVR Engine is responsible for finding the optimum solution for both VVO and CVR problems in real-time. Thus, the objective of the Volt/VAr optimization algorithm can be formulated as minimizing the real-time loss costs of distribution network at each VVO/CVR time interval. Equations (1), (2) and (3) give the objective function of proposed VVOE.

$$Min\, S_{Loss} = Min\,(C_{loss} \times S \times h_t) = Min\,(C_{loss}(\sqrt{P_{loss,total}^2 + Q_{loss,total}^2})h_t) \quad (1)$$

$$P_{loss,total} = \sum_{n=1}^{N} P_{loss,n,t} \quad (2)$$

$$Q_{loss,total} = \sum_{n=1}^{N} Q_{loss,n,t} \quad (3)$$

Where,

S_{Loss}: Total loss cost (\$), C_{Loss}: Loss cost (\$/kVAh), S: Total loss (kVA), h_t: Time (h), $P_{loss,total}$: Total active power loss, $Q_{loss,total}$: Total reactive power loss, $P_{loss,n,t}$: active power loss of node-n at time-t, $Q_{loss,n,t}$: Reactive power loss of node-n at time-t, N : number of nodes.
The VVO/CVR algorithm constraints in real-time intervals can be written as follows:

a) Voltage of the nodes:

$$V_{n,t}^{min} \leq V_{n,t} \leq V_{n,t}^{max} \xrightarrow{ANSI} 0.95 \text{ p.u} \leq V_{n,t} \leq 1.05 \text{ p.u} \quad (4)$$

Where, $V_{n,t}$: voltage of node-n at time-t, $V_{n,t}^{min}$: minimum voltage of node-n and $V_{n,t}^{max}$:maximum voltage of node-n at time-t

b) Active power output of nodes:

$$P_{n,t}^{min} \leq P_{n,t} \leq P_{n,t}^{max} \quad (5)$$

Where, $P_{n,t}$: active power of node-n at time-t

c) Reactive power output of nodes:

$$Q_{n,t}^{min} \leq Q_{n,t} \leq Q_{n,t}^{max} \quad (6)$$

Where, $Q_{n,t}$: reactive power of node-n at time-t

d) Distributed Generation active power constraint:

$$P_{DGn,t}^{min} \leq P_{DGn,t} \leq P_{DGn,t}^{max} \quad (7)$$

Where, $P_{DGn,t}$: active power of DG of node-n at time-t

e) Distributed Generation reactive power constraint:

$$Q_{DGn,t}^{min} \leq Q_{DGn,t} \leq Q_{DGn,t}^{max} \quad (8)$$

Where, $Q_{DGn,t}$: reactive power of DG of node-n at time-t

f) Active power balance based on Optimal Power Flow (OPF):

$$\forall t \in T,$$

$$P_{n,t} = P_{Gn,t} - P_{Ln,t} = \sum_{m}^{M} V_{n,t} V_{m,t} (g_{nm,t} \cos \theta_{nm,t} + b_{nm,t} \sin \theta_{nm,t}) \quad (9)$$

Where, $m \in M = (n + \delta_n)$, δ_n: set of incident node, $P_{Gn,t}$: active generated power of node-n at time t, $P_{Ln,t}$: active consumed power of node-n at time-t, $V_{n,t}$: voltage of nofe-n at time-t, $V_{m,t}$:voltage of node-m at time-t, $g_{nm,t}$: conductance matrix between bus-n and bus-m, $b_{nm,t}$: susceptance matrix between bus-n and bus-m, $\theta_{nm,t}$: phase angle between bus-n and m in time-t

g) Reactive power balance based on OPF:

$$\forall t \in T,$$

$$Q_{n,t} = Q_{Gn,t} - Q_{Ln,t} = \sum_{m}^{M} V_{n,t} V_{m,t} (g_{nm,t} \sin \theta_{nm,t} - b_{nm,t} \cos \theta_{nm,t}) \quad (10)$$

Where, $Q_{Gn,t}$: reactive generated power of node-n at time t, $Q_{Ln,t}$: reactive consumed power of node-n at time-t

h) System required Power Factor (PF):

$$PF_{n,t}^{min} \leq |PF_{n,t}| \quad (11)$$

Where, $PF_{n,t}$: Power factor of bus-n at time-t

i) Feeder Thermal limit

$$S_{nm,t} \leq S_{nm,t}^{max} \quad (12)$$

Where, $S_{nm,t}$: Power limit of line-nm at time-t

j) Capacitor Bank Switching limit

$$CB_{daily\ sw} = \sum_{t=1}^{T=96} CB_{sw,t} \leq CB_{daily\ sw}^{max} \tag{13}$$

Where, $CB_{daily\ sw}$: daily CB switching limit, $CB_{sw,t}$: CB switching at time-t

k) Transformer and VR tap limits

$$TR_{daily\ tap} = \sum_{t=1}^{T=96} TR_{tap,t} \leq TR_{daily\ tap}^{max} \tag{14}$$

Where, $TR_{daily\ tap}$: daily OLTC or VR tap limit, $TR_{tap,t}$: OLTC or VR tap at time-t

Therefore, the VVO/CVR Engine optimizes the VVO/CVR objective function based on the abovementioned constraints in real-time. The proposed real-time algorithm is presented in Fig. 2.

First, the VVOE receives its required real-time data from IA. If the data is equal to the data of previous time step, system configuration will not change but, if the required data isn't equal to the previous time interval data, the VVO algorithm will begin to solve the real-time VVO/CVR based on Eq. (1) to Eq. (14). The method for reaching the optimal solution is highly dependent on the settings that distribution network operator expects from the system at each time stage. This setting can be the amount of loss reduction in the network or the required Power Factor (PF) at each real-time interval. System operator can regulate specific desired settings for each load time (light load, mid-load and/or peak load times) in order to configure the network optimally.

Thus, VVOE confines the VVO/CVR problem to the substation primarily and if the desired solution is obtained, it will send the optimal solution to the IA as the new reconfiguration command. Otherwise, the VVOE will solve the VVO/CVR considering other system Volt/VAr control device candidates along the feeder such as CBs and/or VRs. Nowadays, distributed generations can assume different roles in smart microgrids. Considering the type, the main task and the operational strategy of a DG (parallel, standby, island) and the effectiveness factor of it in VVO/CVR can be determined. Therefore, if the system reaches a better result when DGs can participate in VVO/CVR, the algorithm will try to check the availability of DGs for VVO/CVR based on their priorities. If all the VAr injection and voltage improvement candidates in the system are applied and the system still have not reached the desired setting, the VVOE will aske the algorithm to offer the closest feasible solution to the setting. After all algorithm steps, if the algorithm doesn't reach the optimal solution, it will send the report to DMS and report the infeasible solution as well as computing time of VVO/CVR problem. In this case (that rarely happens), alternative optimization techniques for solving VVO/CVR will be helpful. If there is not sufficient time for solving the problem again, the algorithm will ask the system to keep its previous time step configuration until the next time step. Hence, the proposed real-time algorithm solves the VVO/CVR problem in an efficient, reliable and smartgrid adaptive technique.

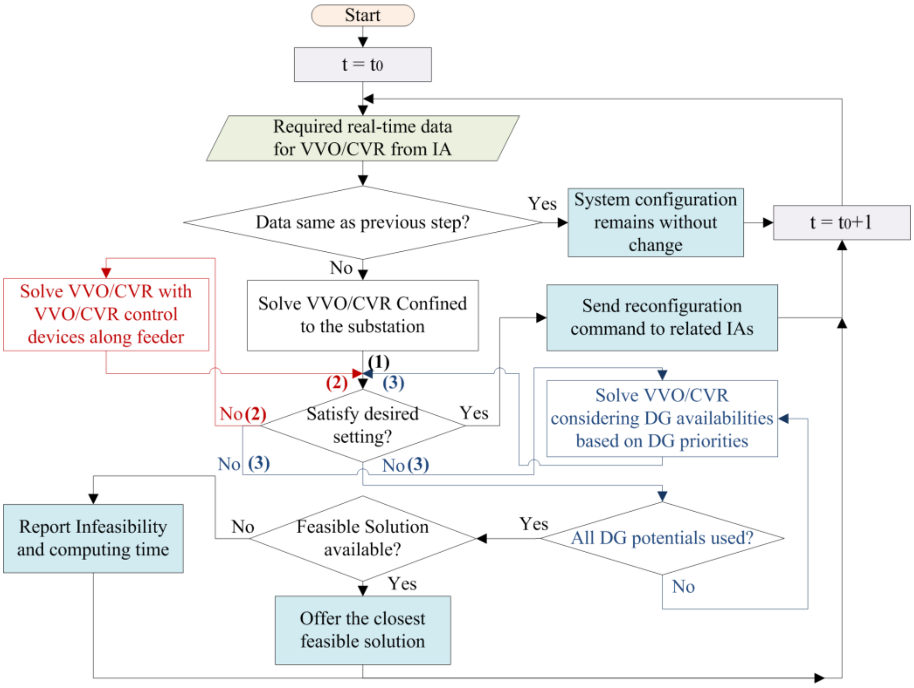

Fig. 2. Proposed real-time optimization algorithm for VVO/CVR

As discussed, the main advantage of the proposed algorithm is its ability to employ most of the smart distribution network capability for an integrated VVO/CVR in real-time. Moreover, the basic structure of this algorithm can be helpful in designing a real-time algorithm with a predictive structure. In this structure, the algorithm can predict the VVO/CVR modes for the next time interval ($t = t + 1$) based on real-time measured data, seasonal and historical data of distribution network nodes. Then, it compares the predicted and the real-time results in $t = t + 1$ and offers the best optimal network configuration. Hence, this algorithm can be used as one of the efficient VVO/CVR algorithms. Fig. 3 depicts the predictive part of the algorithm.

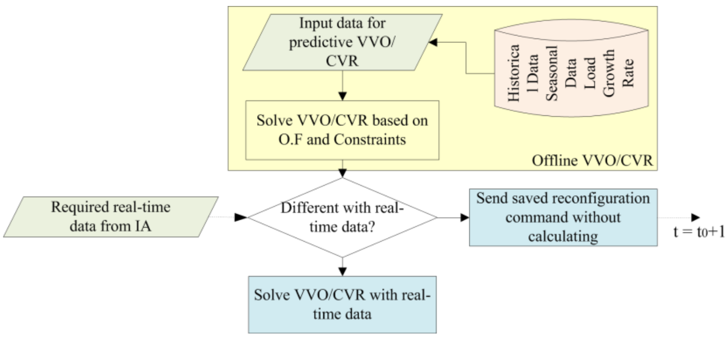

Fig. 3. Predictive part of offered VVO/CVR Engine

3. Case Study and Results

3.1. The Effects of Proposed VVO/CVR in British Columbia Institute of Technology (BCIT) Case Study

In this section, a BCIT case study is fully assessed. The part of the BCIT distribution network studied here consists of 21 nodes, two main substations (Sub-F and Sub-E) and various types of loads. Moreover, the network has different distributed generation sources such as: Micro-turbine, Roof-top PVs and Flywheel Energy Storage System (FESS). Fig. 4 presents the SLD of the BCIT case study.

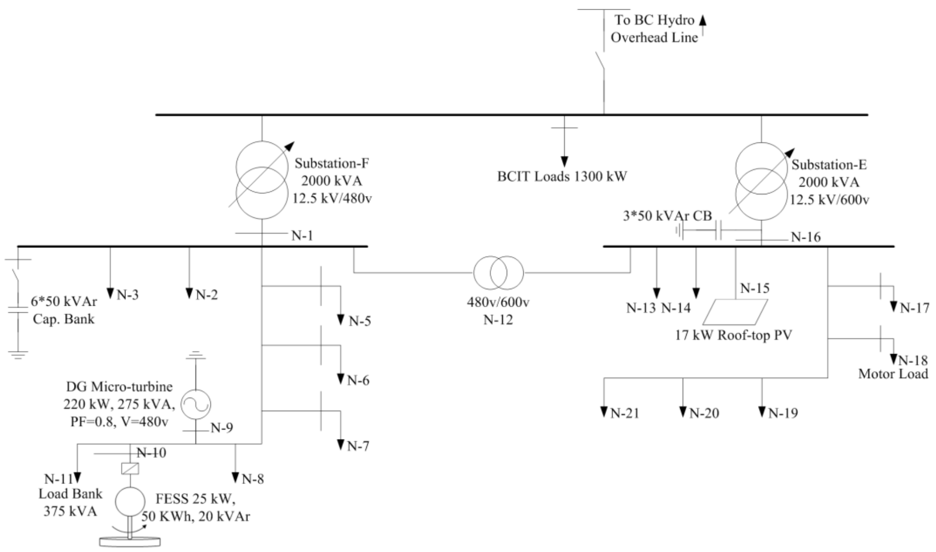

Fig. 4. Single Line Diagram of Considered Case Study

As shown in Fig. 4, both substations have a 2000 kVA transformer. Sub-E has a capacitor bank unit with 150 kVA capacity (3*50 kVA). It is assumed that both transformers have tap-changers with 17 tap-steps that can regulate the voltage between -%5 to +%5. Hence, each tap step can regulate the voltage plus or minus % 0.625. In addition, 1300 kW total load which is located at the MV side of Sub-E is considered in the simulation. The proposed VVO/CVR is performed in 15-minutes time intervals for a complete day (96 time stages). The captured values of active and reactive power of nodes as well as load types are presented in TABLE II. At the low voltage side of Sub-F, a micro-turbine (220 kW, 275 kVAr) is placed which operates in parallel with the network. In addition, the feasibility of installing a 25 kW, 50 kWh FESS with 20 kVAr injecting power on node-10 is under study. At the LV side of Sub-E, a roof-top PV with 17 kW total generation is placed. According to the geographical position of BCIT campus (Burnaby: -123.02E, 49.26N), the operational hours of a solar PV in average is around 3.8 hours/day/year. According to the previous records, generating capacity of the roof-top PV in the best insolation condition will be equal to 11.2 kW which is considered in simulation.

TABLE II CURVE TYPES, ACTIVE AND REACTIVE POWERS OF LOADS IN BCIT CASE STUDY

Node Number	Load Type	P (kW)	Q (kVAr)	Node Number	Load Type	P (kW)	Q (kVAr)
N-2	1 Com.	0.03	0.015	N-13	3 Com.	0.065	0.032
N-3	1 Com.	0.025	0.012	N-14	3 Com.	0.015	0.008
N-5	1 Com.	0.08	0.040	N-17	3 Com.	0.015	0.008
N-6	1 Com.	0.065	0.032	N-18	5 Motor Load	0.015	0.009
N-7	2 Com.	0.015	0.007	N-19	3 Com.	0.015	0.008
N-8	2 Com.	0.015	0.007	N-20	3 Com.	0.01	0.005
N-11	4 Load bank	0.72	0.375	N-21	3 Com.	0.015	0.008

The studied network consists of different load types. Fig. 5 depicts different load profiles of BCIT loads which is obtained from measured data. As presented in Fig. 5 and TABLE II, network's typical loads are of three different types which are mainly commercial loads (load types: 1, 2, 3). Moreover, the load curve of the existing load bank (load type-4) at node-11 is different from other typical loads. For the load bank, it is shown that it has been swithced on at the beginning of working hours of laboratory (10 A.M) and it has been switched off at 6 :30 P.M. Additionally, an inductive motor load exists at node-8 of the system. This three phase motor has 20 hp (15 kW) rated power with 1800 r.p.m. It has 0.86 Power Factor (reactive power is equal to 8.9 kVAr) at ¾ full load. The load curve of the motor load (load type-5) is as follows: It has been switched on at 10 A.M and operates at 0.92 of its nominal mode and it has been switched off at 7 P.M.

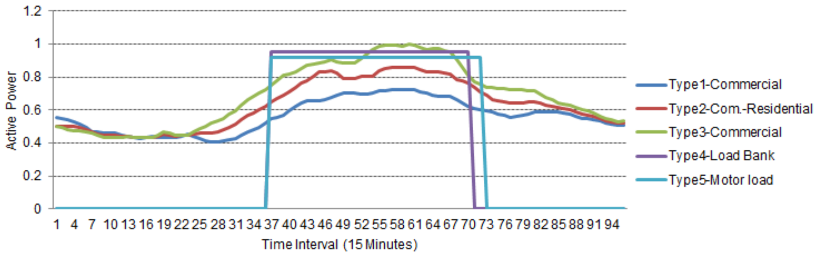

Fig. 5. Load profile types of the Case Study

The effect of proposed real-time VVO/CVR algorithm is evaluated. First, the initial condition (dumb mode) of BCIT distribution network without VVO/CVR implementation is presented and then, the real-time VVO/CVR is studied in two modes (confining to the substations and distributing along the feeder). The applied optimization technique for the VVO/CVR engine is improved GA considering Eq. (1) to Eq. (14).

Fig. 6 presents the system loss curve in three different scenarios: a) without VVO/CVR, b) VVO/CVR confines to the substations and c) VVO/CVR options within substations and along distribution feeder. As pointed out in previous section, VVO/CVR engine can optimize the network based on system operator desired settings. In the first case, the desired setting for loss minimization at peak is considered to be equal to 120 kW. Hence, the algorithm is found for the VVO/CVR confined to the system substations. In the second scenario, the desired setting for the system loss at peak is changed to 100 kW. Thus, the algorithm used other VAr injection candidates along BCIT feeder as well as substation Volt/Var control devices. On the other hand, VVO/CVR algorithm regulates the voltage profile of the network. Fig. 7 illustrates the voltage profile of all BCIT nodes in four cases: a) dumb system without VVO/CVR, b) VVO/CVR inside substations, c) VVO/CVR with only VAr injection CB candidates and d) Integrated real-time VVO/CVR.

As observed in Fig. 7, some of the voltage nodes are out of ANSI band in the first case. In case (b), this issue is solved by VVO/CVR engine. In this case, the Tap position of Transformer-1 is equal to 0.99375 and the capacitor bank of Sub-E is employed in full capacity (150 kVAr). If capacitor banks are present along distribution feeder, system voltage profile improves significantly. In this step, CVR tries to reduce the voltage of some nodes by applying OLTCs and existed VRs in order to conserve energy. This condition is shown in case (d). In this case, VVO/CVR algorithm set the Transformer-1 tap position at 1.01875 and set the Transformer-2 tap position at 1. Moreover, it recommends a VR close to node-12. The tap changes of this VR are shown in Fig. 8. Furthermore, Fig. 9 presents the VAr injection point candidates at each real-time interval.

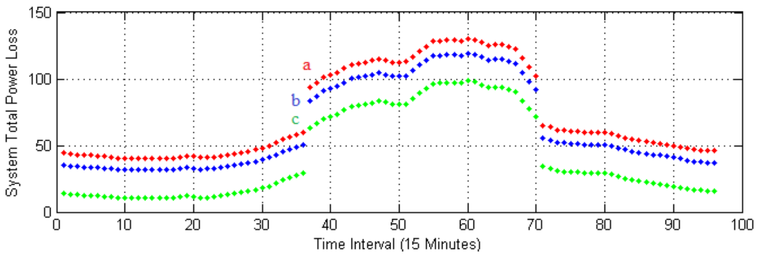

Fig. 6. System Loss Curve for Different Scenarios: a) without VVO/CVR, b) VVO/CVR confines to the substations and c) VVO/CVR implementation within substations and along distribution feeder

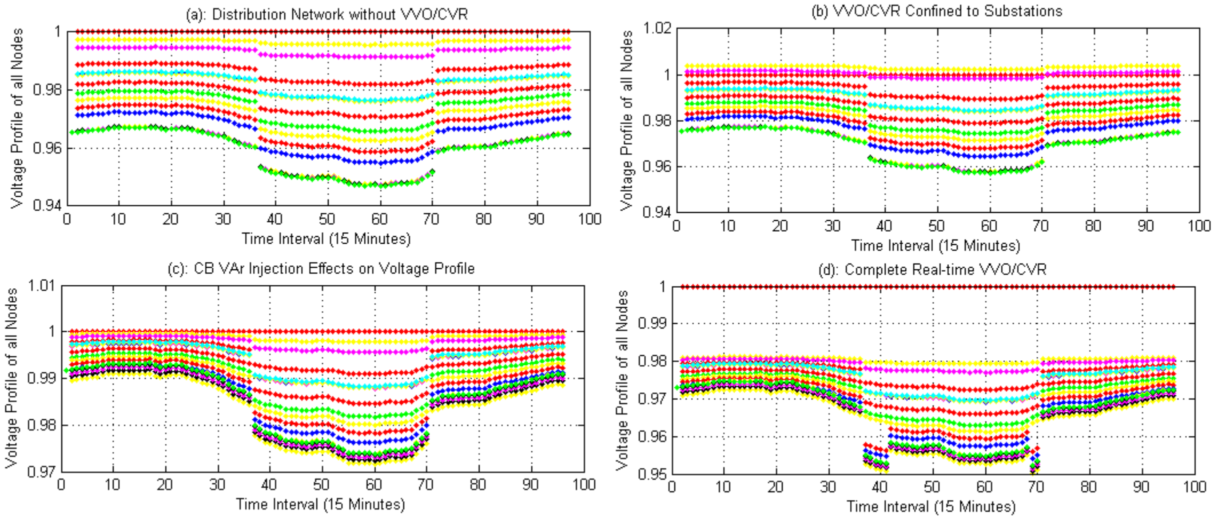

Fig. 7. Voltage Profile of All Nodes of the Case Study in Different Scenarios

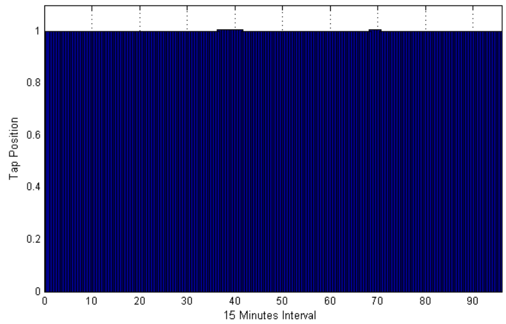

Fig. 8. Tap changes of the VR during a full day operation

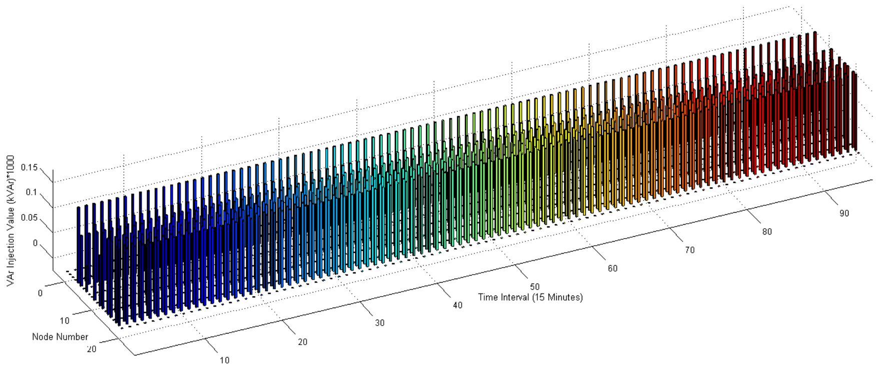

Fig. 9. CB VAr injection point candidates at each real-time interval

3.2. The Effect of Flywheel Energy Storage System on the System VVO/CVR

In this sub-section the effect of FESS on system Volt/VAr optimization is studied. It should be mentioned that the effect of other DG sources such as Micro-turbine (as a generating unit which operates in parallel with distribution network) and roof-top PV are considered in the main VVO/CVR. Thus, the Flywheel role in real-time VVO/CVR cycles is assessed. As noted, the system has a Flywheel Energy Storage System which is able to inject 25 kW active and 20 kW reactive powers to the grid every two hours (50 kWh, 40 kVAh). After discharging and transmitting power to the grid, FESS will be back to the charge mode. One of the substantial features of new flywheel energy storage technology is that it lets operators to regulate and control the charge and discharge cycles of a FESS. Therefore, Fig. 10 illustrates the effect of FESS in VVO/CVR loss reduction and assumed charge/discharge cycles of it. As shown in Fig. 10, FESS is available for VVO/CVR in several time stages based on its regulated cycles and assist VVO/CVR to reduce the system loss considerably. Based on determined priority, VVO/CVR engine asks FESS to participate in VVO/CVR at each real-time stage. It checks FESS availability every 15 minutes. If FESS is available, the VVO/CVR algorithm will choose FESS as one of the Volt/VAr control devices in its problem.

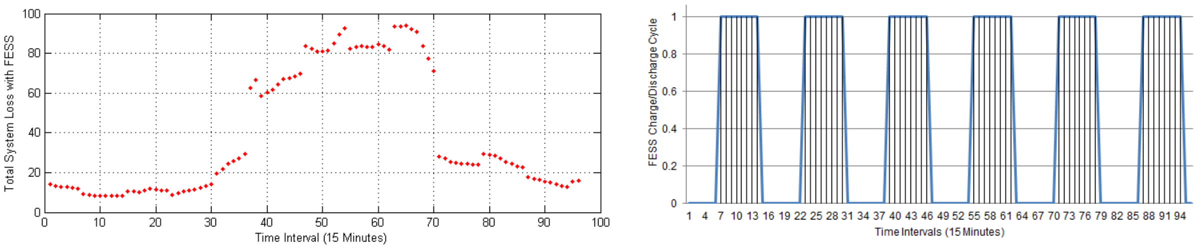

Fig. 10. The Effect of FESS on VVO/CVR and its Charge/Discharge Cycle

As a result, the proposed VVO/CVR approach optimized the BCIT network in a reliable and efficient way in real-time. TABLE III gives the total and comparable results of the proposed VVO/CVR engine. Considering the results of TABLE III and the fact that the mean approximated energy cost for BCIT campus is equal to 6 Cents per kWh, VVO/CVR can save costs for BCIT. If VVO/CVR is being limited to the substations, it is possible to save 926.8182 kW-15minutes of energy and CAD 13.90227 per day as energy conservation. If the VVO/CVR algorithm is being implemented along distribution feeder, the values will be raised (2929.465 kW-15minutes of energy and CAD 43.94197 as energy conservation). Finally, if the flywheel storage system effect is being considered, the conservation values will be 3266.567 kW-15minutes of energy and CAD 48.99851. By simple approximations, one can conclude that it is possible to conserve considerable energy and save costs in BCIT campus by applying proposed real-time and smartgrid adaptive VVO/CVR approach. It is clear that this approach can help campus economy as well as utility to conserve more energy.

TABLE III RESULTS OF THE VVO/CVR FOR THE CASE STUDY

	Network without VVO/CVR	VVO/CVR Confined to Substations	VVO/CVR	FESS
Total daily loss (kWh)	1750.0007	1518.29625	1017.63475	816.64175
Cost Saving (CAD)	0	13.90227	43.94197	48.99851

4. Conclusion

This paper presented a new real-time smartgrid adaptive VVO/CVR approach based on distributed command and control structure that can minimise distribution network loss and improve voltage profile of nodes. The propsoed algorithm has numerous abilities such as considering existing Volt/VAr control components based on operator desired settings, ability to determine VAr injection points along the feeder, optimizing VVO/CVR problem in real-time, extendibility of the algorithm to be predictive and smartgrid adaptable structure based on the availability of distributed generation sources.

The paper discussed the structure of the algorithm in regards to the intelligent distribution network and distributed command and control structure. The related computations for the algorithm, objective function and the constraints are explained in detail and BCIT distribution network is used to study the applicability and the accuracy of the VVO/CVR algorithm.

The results proved that VVO/CVR is capable of optimizing system in different stages and it can take advantage of distributed generation in smart microgrids. Hence, at each real-time stage, the algorithm could reduce system loss as well as improve voltage profile.

Given the fact that each distribution network node may be smart with self-healing in the future, the proposed algorithm is compliant with both existing and future frameworks. This can help distribution networks to achieve higher degrees of energy conservation and voltage regulation at each real-time interval through an integrated VVO/CVR sub-system. Therefore, both customer and utility can benefit from a real-time VVO/CVR. Consumer can enjoy a more reliable network with less expenses and utility can conserve more energy by implementing the proposed VVO/CVR approach.

BIBLIOGRAPHY

[1] ANSI Standard C 84.1 – 1995, "Electrical Power Systems and Equipment – Voltage Ratings".

[2] CAN 3-C235-83(R2000) Standard.

[3] S. Auchariyamet and S. Sirisumrannukul "Volt/VAr Control in Distribution Systems by Fuzzy Multiobjective and Particle Swarm" (6th International conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology, ECTI-CON, Pattaya, Thailand, May 2009).

[4] A. Rahideh, M. Gitizadeh and A. Rahideh "Fuzzy Logic in real time voltage/reactive power control in FARS regional electric network" (Electric Power System Research number 76 February 2006 pages 996-1002).

[5] B. Alencar de Souza and A. M. F de Almeida "Multiobjective Optimization and Fuzzy Logic Applied to Planning of the Volt/Var Problem in Distribution Systems" (IEEE Trans. Power Systems volume 11, August 2010 pages 1274–1281).

[6] A. T. Saric and A. M. Stankovic "A Robust Algorithm for Volt/Var Control" (Power System Conference and Exposition, PSCE09, IEEE PES, Seattle, WA, 2009)

[7] G. A. Bakare, G. Krost, K. Venayagamoorthy and U. O. Aliyu "Comparative Application of Differential Evolution and Particle Swarm Techniques to Reactive Power and Voltage Control" (International Conference on Intelligent Systems Applications to Power Systems, ISAP 2007, Niigata, Japan, Nov. 2007).

[8] D. H. Spatti, I. N da Silva, W. F. Usida and R. A. Flauzino "Real-Time Voltage Regulation in Power Distribution System Using Fuzzy Control" (IEEE Transactions on Power Delivery volume 25 April 2010 pages 1112–1123).

[9] R. Singh, F. Tuffner, J. Fuller and K. Schneider " Effects of Distributed Energy Resources on Conservation Voltage Reduction (CVR)" (Power and Energy Society General Meeting, IEEE, San Diego, CA, USA, July 2011).

[10] S. Auchariyamet and S. Sirisumrannukul "Optimal Daily Coordination of Volt/VAr Control Devices in Distribution Systems with Distributed Generators" (45th International Universities Power Engineering Conference (UPEC), Cardiff, Wales, September 2010).

[11] W. Huang, G. X. Xia, N. Kobayashi and X. Xu "Distributed Generation on Distribution System Voltage Regulation: An Optimization-based Approach" (Power and Energy Society General Meeting, IEEE, Minneapolis, MN, USA, July 2010).

[12] E. Jauch "Volt/Var Management? An Essential "SMART" Function," (Power System Conference and Exposition, PSCE09, IEEE PES, Seattle, WA, March 2009).

[13] N. Markushevich "The Benefits and Challenges of the Integrated Volt/Var Optimization in the Smart Grid Environment" (Power and Energy Society General Meeting, IEEE, San Diego, CA, USA, July 2011).

[14] R. W. Uluski "VVC in Smart Grid Era," (Power and Energy Society General Meeting, IEEE, Minneapolis, MN, USA, July 2010).

[15] E. T. Jauch "Possible Effects of Smart Grid Functions on LTC Transformers" (IEEE Transactions on Industry Applications volume 47, April 2011, pages 1013–1021.

[16] V. Dabic, S. Cheong J. Peralta, and D. Acebedo "BC Hydro's Experience on Voltage VAR Optimization in Distribution System" (Transmission and Distribution Conference and Exposition, 2010 IEEE PES, New Orleans, LA, USA, April. 2010).

[17] H. Fakham, F. Colas and X. Guillaud "Real-time Simulation of Multi-Agent System for Decentralized Voltage Regulation in Distribution Network" (Power and Energy Society General Meeting, IEEE, San Diego, CA, USA, July 2011).

[18] A. Ajaja "Reinventing Electric Distribution," (IEEE Potentials volume 29 Jan.-Feb. 2010 pages 29-31).

[19] Electric Power Research Institute (EPRI), "EPRI Smart Grid Demonstration Update," (An EPRI Progress Report, March 30, 2011).

[20] Giuseppe Stanciulescu, Hassan Farhangi, Ali Palizban, Nikola Stanchev "Communication Technologies for BCIT Smart Microgrid" (Presented at IEEE PES General Meeting, Washington DC, Jan 2012).

[21] Hassan Farhangi “Campus Based Smart Microgrid at British Columbia Institute of Technology in Vancouver, Canada” (Presented at Cigré 2011 Bologna Symposium, Italy, Sept. 2011).

[22] Ali Palizban, Hassan Farhangi “Low Voltage Distribution Substation Integration in Smart Microgrid” (IEEE 8th International Conference on Power Electronics, Jeju Island, South Korea, June 2011).

[23] Hassan Farhangi “The Path of Smart Grid” (IEEE Power & Energy Magazine volume 8 number 1 January 2010 pages18-28.

[24] Hassan Farhangi “Intelligent Microgrid Research at BCIT” (IEEE Electric Power Conference, EPEC’08, Vancouver, Canada, Oct. 2008).

[25] S. Lefebvre, G. Gaba, A-O. Ba, D. Asber, A. Richard, C. Perreault and D. Chattrand “Measuring the Efficiency of Voltage Reduction at Hydro-Quebec Distribution” (Power and Energy Society General Meeting, IEEE, 21st Century, Pittsburg, PA, USA, July 2008).

[26] A. Ajaja “Volt and Var Control for Energy Efficiency at Hydro-Quebec Distribution” (Metering International, SmART Energy, Issue 3, 2011).

[27] H. Fakham, A. Ahmidi, F. Colas and X. Guillaud “Multi-Agent System for Distributed Voltage Regulation of Wind Generators Connected to Distribution Network” (Innovative Smart Grid Technologies Conference Europe (ISGT Europe), IEEE PES, Gothenburg, Sweden, Oct. 2010).

[28] Thomas. L. Wilson “Measurement and Verification of Distribution Voltage Optimization Results for IEEE Power & Energy Society” (Power and Energy Society General Meeting, IEEE, Minneapolis, MN, USA, July 2010).

[29] M. J. Krok and S. Genc “A Coordinated Optimization Approach to Volt/VAr Control for Large Power Distribution Networks” (American Control Conference on O'Farrell Street, San Francisco, CA, USA, June 29 – July 2011).

[30] H. Diaz., I. Harnisch, R. Sanhueza and R. Olivares “Feeder Reconfiguration and Capacitor Placement in Distribution Systems: An Approach for Simultaneous Solution Using a Genetic Algorithm” (Ingeniare. Revista chilena. Ingenierfa journal volume 18 number 1, April 2010 pages 144-153).

[31] G. Svenda, V. Strezoski, Z. Simendic and V. Mijatovic “Real time Voltage Control Integrated in DMS” (20th International Conference on Electricity Distribution, CIRED, Prague, June 2009).

[32] A. Mohd “Supervisory control and energy management of an inverter-based modular smart grid” (Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES, 15-18 March 2009).

[33] A. Vaccaro, G. Velotto and A. F. Zobaa “A Decentralized and Cooperative Architecture for Optimal Voltage Regulation in Smart Grids” (IEEE Transactions on Industrial Electronics volume 58, number 10, October 2011, pages 4593-4602).

[34] H. Johal, Wei Ren, Yan Pan and M. Krok “An integrated approach for controlling and optimizing the operation of a power distribution system” (2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Gothenburg, Sweden, Oct. 2010).

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