A Design of a Reactive Power Management System

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Abstract: A basic framework of reactive ancillary services under the power market considering reactive power as compensatory consumption is investigated in this analysis. The given Distributed Generators (DGs) are induced and used as sources of reactive power and optimize the overall distribution operation considering reactive power delivery costs. A basic framework of reactive ancillary services under the power market considering reactive power as compensatory consumption is investigated in this analysis. Hence, the proposed model reduces maintenance costs of the distribution network and improves the voltage level of the distribution network by considering the reactive power adjustment capability of the DG.

Keywords: Power Market, Reactive Power Service, Value Of Reactive Power Resource, Pricing Of Reactive Power.

I. Introduction

To resolve the conflict between increasing resource scarcity and strong economic growth, the world has begun to develop new energy technologies on a large scale. New energy technologies represented by distributed photovoltaic power generation have been intensively promoted and applied. When the photovoltaic is connected to the high penetration distribution network system, the distribution network system becomes a multi-source system structure and the power flow changes from one-way to two-way. The magnitude, flow direction and distribution characteristics of short-circuit current vary to some extent [1]. When the photovoltaic output fluctuates, isolated devices are likely to malfunction, making it easy to reach the upper limit of the number of actions.

For voltage changes caused by such small fluctuations, it is not economical to use discrete device mode of operation. Using photovoltaics to coordinate different adjustment devices is beneficial to reduce the number of actions of different discrete devices. When the line fails, the sensitivity and selectivity of the relay protection are greatly affected [2]. By rationally optimizing the location and capacity of distributed photovoltaic energy sources in the distribution network, the grid voltage can be increased and the stability of the grid can be increased.

A high proportion of photovoltaic access will develop the distribution network from a traditional single point radial grid structure to a complex network structure of multiple power sources. At the same time, the current and voltage distribution may become more complex and variable due to their seasonal changes and short-term fluctuations [3]. After the grid connection of high permeability distributed photovoltaic power generation, the voltage limit may be exceeded.

In deregulated power systems, real energy transactions are conducted through electricity markets overseen by system operators. Research and policy making for the provision of ancillary services through the electricity market is also becoming relevant in the context of deregulation. This is because, when private generation companies (GENCOs) participate in ancillary service markets, they play an important role in maintaining system parameters within permissible limits. Reactive power services are considered an important ancillary service in this regard due to its contribution to maintaining system wide bus voltage and adequate reserve in the system.

Reactive power ancillary service is required to

- Satisfy reactive power load
- Control system wide bus voltage
- Relieve transmission block
- Reduce network loss
- Provide sufficient reserve to ensure security

In 1991, the concept of real-time reactive power pricing based on optimal power flow. Only the real power generation cost is considered in AC-OPF to determine the marginal cost of reactive power. It is observed that reactive power cost is more sensitive to change in voltage magnitudes than transmission congestion and generator limitations. Reactive power pricing can be done in real time through the steps listed below.

- Pay nothing for operation within a control range
- Pay unit specific opportunity cost
- Pay marginal cost price (MCP) based on auction.
- Pay based on a predetermined reactive power pricing formula – adopted in UK and India.

However, a major disadvantage of Max Continuous Power (MCP) based auctions is the potential for GENCOs to exercise market power. Hence, opportunity cost based pricing is generally adopted. Various reactive power market and pricing mechanism is summarized. Heuristic methods like genetic algorithm, particle swarm optimization are used to solve ACOPF to determine the cost of reactive power. Reactive power marginal prices are found to be highly volatile when considering reactive power production cost, active power production cost and capital cost of capacitors in AC-OPF. To avoid volatility of reactive power marginal pricing, two level market-reactive energy market and reactive capacitive market. To avoid using market power, it is suggested that the reactive power cost curve for each generator be estimated from day-ahead market bid data by the transmission operator. A cost-based reactive power pricing model is formulated and the OPF is solved using sequential quadratic programming. By minimizing the reactive power generation cost, the optimal generator voltage for operation is determined. Expected Payout Function (EPF) is penalized which takes into account the availability of generating unit, lost opportunity cost and loss of reactive power in the generating unit. However, GENCOS was observed to exercise market power. The main contribution of this paper is a real time pricing mechanism for reactive power considering the system voltage which is effective in satisfying the reactive power load, controlling the system wide bus voltage and providing sufficient reserve for safe operation. Marginal value based marginal pricing proposed for reactive power can reduce volatility and market power to some extent. The proposed real-time reactive power pricing model is based on a defined value function for the reactive power requirement in the system.

The optimal reactive model under power market can be further divided into the two categories: the pricing of reactive ancillary services and the economic reactive dispatch considering its cost[4] and Frequency control, voltage support and various ancillary service. The optimal reactive dispatch model aiming at minimizing the operation cost is proposed [5] and the cost of reactive operation of conventional generation. Doubly Fed Induction Generators (DFIGS) and PhotoVoltaic (PV) are analyzed. The cost function of different type of Wind Turbines (WTs) in reactive ancillary services market is investigated and then the multi-objective model is presented to minimize the payments of the distribution system operator to the DG.

II. Literature Survey

B. Tamimi, C. A. Canizares and S. Vaez-Zadeh, et.al [6] explained the different models for representing reactive power limits in these optimization problems are then presented, concentrating in particular on the proper modeling of the generators' capability curves as terminal voltages change, which has been identified as a shortcoming of previous studies. Comparative numerical analyses of the effect of various reactive power limit models in maximum loading and active and reactive power dispatch and pricing levels are presented and discussed, to thus quantify the effect these various limit representations have on the corresponding results. Two test systems, namely, the CIGRE-32 benchmark system and a 1211-bus dispatch model of a European network, are used for numerical studies. The presented results show that in most OPF applications, the improvement on the reactive power limits representation lead to subtle differences at the cost of increased computational complexity, which in some cases may be difficult to justify in practice.

A. Rabiee, H. Feshki Farahani, M. Khalili, J. Aghaei and K. M. Muttaqi,, et.al [7] describe reactive power plays an important role in distribution networks to improve network conditions such as voltage profile improvement and loss reduction. Plug-in Electric Vehicles (PEVs) are mobile sources of active and reactive power, capable of being participated in energy market, and also in reactive power market without battery degradation. Active and reactive powers are coupled through the ac power flow equations and branch loading limits, as well as PEVs and synchronous generators capability curves. This paper presents a coupled energy and reactive power market in the presence of PEVs. The objective function is threefold, namely offers cost (for energy market), total payment function (for reactive power market), and lost opportunity cost, all to be minimized. The effectiveness of the proposed coupled energy and reactive power market is studied based on a 134-node microgrid with and without PEV participation.

M. De and S. K. Goswami, et.al [8] explains short-term Reactive Power Procurement (RPP) problem assuming an already established real power market. Contributions of this paper are three fold. First, this paper presents three new RPP methods which are formulated as Optimum Power Flow (OPF) problems. OPFs are solved using Artificial Bee Colony (ABC) algorithm as population based stochastic solution methods are more suitable for solving reactive power optimization problem. Second, a detailed analysis of voltage stability for proposed RPP problems are performed for both normal and contingency condition to find out how these new formulations affect voltage stability. Third, proposed methods are compared with the classical RPP formulations, e.g., Minimization of L-index and loss Minimization. Finally results are reported for both test system and a large practical system.

Q. Hui, Y. Teng, H. Zuo and Z. Chen, et.al [9] explains robust dynamic evolutionary optimization of the reactive power system in interconnected systems under fluctuating and uncertain wind power conditions. Therefore, the rapid collaborative optimization of reactive power flow and the exchange of reactive power between tie lines between provincial power grids are realized. The analysis was made by taking four interconnected large-scale provincial power grids of Eastern Mongolia, Jilin, Liaoning and Shandong as an example. The simulation results demonstrate the effectiveness and superiority of the proposed reactive power dynamic multi-objective optimization method for interconnected power grids.

S. M. Sadek, W. A. Omran, M. A. M. Hassan and H. E. A. Talaat, et.al [10] fast forward scenario reduction algorithm is used to reduce the number of scenarios with the help of SCENRED/GAMS software. Usually, fuel consumption costs of diesel generators are considered to be dependent on active power generation only. However, neglecting the related reactive power costs might result in increased operation costs and deviations in the dispatches from the optimal solutions. Hence, this paper co-optimizes the costs related to both active and reactive powers of diesel generators. In addition, this study considers the reactive power capability of inverter-interfaced distributed energy resources (DERs). Moreover, the detailed models for the different resources are presented, especially for diesel generators where the actual capability curves are used instead of the widely used box constraints. The problem is formulated as a nonlinear programming problem in the General Algebraic Modeling System (GAMS) software and is solved by the CONOPT solver.
I. El-Samahy, K. Bhattacharya, C. Canizares, M. F. Anjos and J. Pan, et.al [11] explains marginal benefits of reactive power supply from each provider with respect to system security are obtained by solving an Optimal Power Flow (OPF) that maximizes system load ability subject to transmission security constraints imposed by voltage limits, thermal limits, and stability limits. Second, the selected set of generators is then determined by solving an OPF-based auction to maximize a societal advantage function comprising generators' offers and their corresponding marginal benefits with respect to system security, considering all transmission system constraints. The proposed procedure yields the selected set of generators and zonal price components, which would form the basis for seasonal contracts between the system operator and the selected reactive power service providers.

P. Frias, T. Gomez and D. Soler, et.al [12] presents a new approach to design reactive power capacity markets. Under this approach annual auctions to procure reactive power capacity are conducted by the system operator. Two products are defined, reactive power generation and absorption capacity, which can be supplied by different independent VAR sources, such as generators, SVCs, capacitor banks and shunt reactors. Reactive power capacity is allocated using an optimization algorithm that matches capacity bids and system reactive power needs, for peak and low demand hours. The reactive power requirements are calculated taking into account system contingencies and the dynamic performance of the VAR sources under these situations.

J. Yu, W. Yan, W. Li, C. Y. Chung and K. P. Wong, et.al [13] novel AC-DC Optimal Reactive Power Flow (ORPF) model with the generator capability limits is proposed. The objective is to minimize the total cost of generator reactive and active power outputs paid by an independent transmission company. In the model, the generator operation area is divided into four parts with each one having a different reactive output cost function. The boundaries between the four parts change with operation states of generators and are unfixed.
J. H. Tovar Hernandez, G. Gutierrez Alcaraz and R. A. Solera Urcuyo, et al [14] explains that reactive power and voltage control service is essential for power system operation. Its pricing should reflect the locational and the differentiated benefit of voltage regulation and reactive power reserves for contingency supporting, so commonly this service is not supplied throughout market mechanisms as the active power, but by considering it as a regulated service with recognized costs. In order to reflect these properties, the power system could be separated into some nonover-lapping reactive power control areas such as the voltage profile of each one of them is mainly controlled by the reactive power sources in that area.

E. Sahraie, A. Zakariazadeh and M. Gholami, et.al [15] proposed method aims at enhancing the social welfare index, improving the demand-side management, controlling the market power potential and decreasing destructive effects of market players' collusion, simultaneously. To analyze the performance of the proposed clearing method, different conditions of the power network including the peak load of the network, the presence of private sensitive loads and multilevel tariffs of the demand has been developed. The proposed method is tested on the 24-bus IEEE Reliability Test System (RTS) and is solved by a Genetic Algorithm (GA) with MATLAB. Also, the Nondominated Sorting Genetic Algorithm (NSGA-II) is used to carry out a comparison with the results of the GA method in similar situations.

F. Hinz and D. Möst, et.al [16] described decentralizing energy systems require renewable energy sources to assume a higher degree of system responsibility. Concerning voltage stability and reactive power management, wind and PV parks connected to 110 kV grids are technically capable of providing reactive power. A controllable and situation-dependent feed-in depending on the respective situation could not only reduce grid losses in the distribution grid, but also facilitate a flexible reactive power exchange with the transmission grid in order to support the voltage stability of the system.

P. Chitkara, J. Zhong and K. Bhattacharya, et.al [17] proposes a mathematical model to simulate the strategic behavior of generators supplying reactive power while considering the system operator's schedule. The proposed method can be used by the regulator to simulate the market behavior in the reactive power supply. We further study how regulatory policies affect the strategic behavior. An alternative price cap method has been proposed and tested in the numerical example to mitigate the effect of strategic behavior of generators in reactive power procurement by the system operator. The numerical examples are tested on the Nordic 32-bus system.

X. Chen and Y. Li, et.al [18] provides the reactive power reference for the DG to guarantee the consistency of the frequency variation trends caused by both active and reactive power mismatches, thus accelerating the islanding detection speed. In addition, the introduction of the voltage variation into the proposed reactive power control strategy can regulate voltage dynamically in grid-connected mode and further shorten the islanding detection time as well. The simulation results show that the proposed algorithm has the zero NDZ property and can detect islanding rapidly. Moreover, the algorithm also performs effectively for load imbalance conditions as well as for the system with multiple DGs.

S. M. Park and S. -Y. Park, et.al [19] introduces a versatile control scheme for unidirectional ac-dc boost converters for the purpose of mitigating grid power quality. Since most power factor correction circuits available in the commercial market utilize unidirectional ac-dc boost converter topologies, this is an almost no-cost solution for compensating harmonic current and reactive power in residential applications. Harmonic current and reactive power compensation methods in the unidirectional ac-dc boost converter are investigated. The additional focus of this paper is to quantify the input current distortions by the unidirectional ac-dc boost converter used for supplying not only active power to the load but also reactive power. Due to input current distortions, the amount of reactive power injected from an individual converter to the grid should be restricted.

C. Lupangu, J. J. Justo and R. C. Bansal, et.al [20] proposed optimal scheme is designed with a two-stage control algorithm based on VET, forecasted solar insolation, and SoC to easily cope with the load demand variation between low and high prices. In this case, the MPC is implemented to predict the SoC in the PV-battery hybrid system by directly calculating it in the first stage while predicting the values of solar irradiance, load consumption, and electricity price. Furthermore, the proposed MPC is used to account for forecasting errors and acts under the given limits to minimize errors and compensate reactive power during the scheduling process. To validate the performance of the proposed control scheme, the PV/battery system is modeled and implemented in MATLAB/Simulink package. Simulation results demonstrate that the proposed optimal control scheme has better performances under various scenarios such as parameter uncertainties and sudden changes.

III. Reactive Power Management

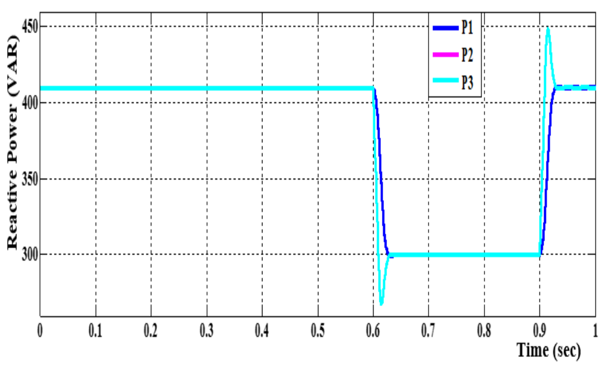
Reactive power supply plays an important role in meeting reactive power demand and maintaining system voltage levels. Additionally, it greatly contributes to ensuring current flow and voltage stability within the system. Therefore, reactive power supplementary services in the electricity market are affected by regional supply, decentralized regulation, different instruments, analysis complexity, etc.

The power plant supplies reactive power to the grid, and the reactive power requirements are borne by the power recipient. For demand for non-generation benefits, power plants are adequately compensated through reactive power costs and market standards. Power plants receive low or without compensation for generating supply requirements. Real-time adjustable reactive power capacity and real-time reactive power prices are reported by power plants participating in reactive power supplementary services that comply with market standards. Combined with the real-time status of the energy system, AVC provides optimal results for each power plant's reactive power output through optimization calculations. In this way, the power plant generates reactive power with optimal results and settles costs with the dispatcher according to the efficiency of reactive power control, reactive power pricing, and actual reactive power output.

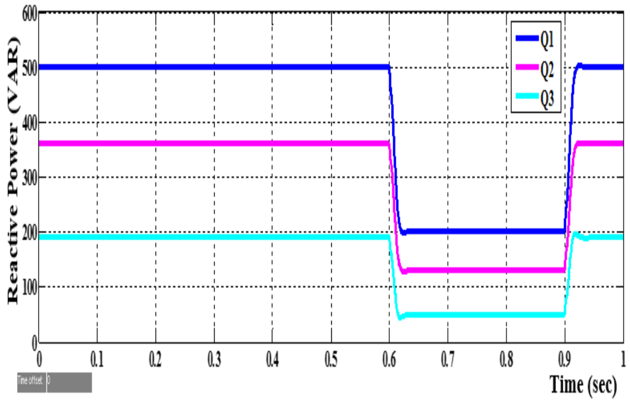
Reactive power is the energy released and stored by capacitors and inductors, measured in VAR or kVAR. This is the energy that flows back into the source from the inductors and capacitors. It is this opposing force that affects the power factor of the circuit. The reactive ancillary service market referred to here is the reactive energy market, which refers to the system paying the price of reactive power equipment to inject or absorb reactive power in the premises to meet the voltage and reactive power demand of the system running.

In the reactive ancillary service market, a cost analysis is first done for various types of units by Distributed Power Producers (DPP) to obtain the reactive power bidding function of generators and the available reactive power capacity during the trading period. The results are then uploaded to the Electricity Market Trading Centre. The trading center ranks the bidding price from lowest to highest ranking. The system forms a reactive bidding curve under different power levels. Finally, determining the reactive power clearing price for each trading session according to the reactive power demand.

IV. Result Analysis

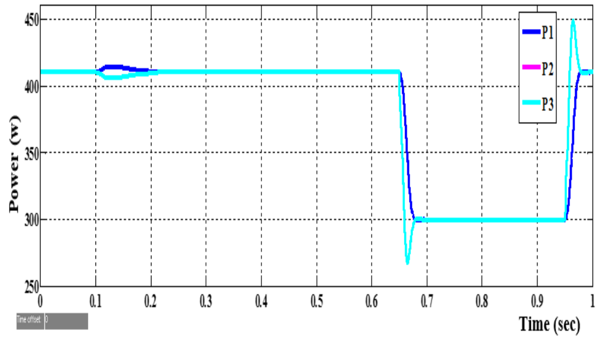


(a)

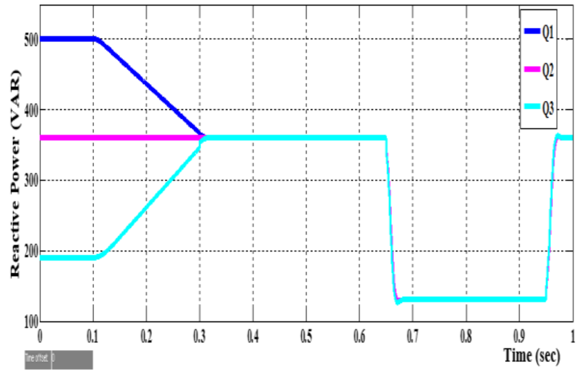


(b)

Fig. 1: Simulation outcomes by normal droop control. (a) Real power. (b) Reactive power.



(a)



(b)

Fig.2: Simulation outcomes of the controller enabled at t = 0.11 s. (a) Real Power. (b) Reactive Power.

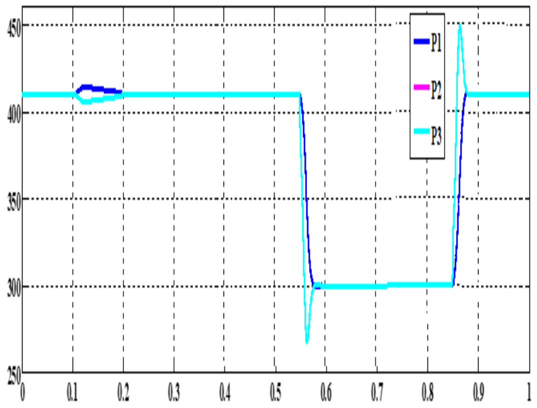
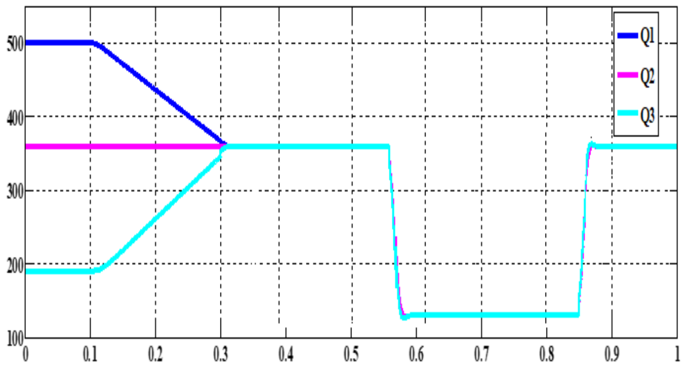


Fig.3: Simulated performance of the proposed controller (activated at t = 0.1 s) with communication failure at 0.55sec (a) Real Power.



(b) Reactive Power.

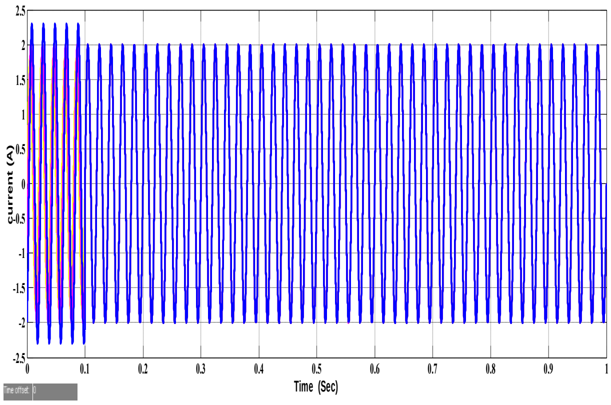


Fig.4: Simulated feeder currents proposed controller (enabling at t=0.1sec)

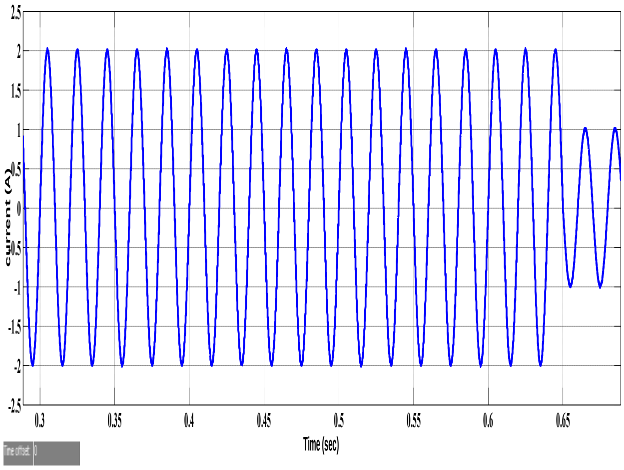


Fig.5: Simulated feeder currents for the proposed system

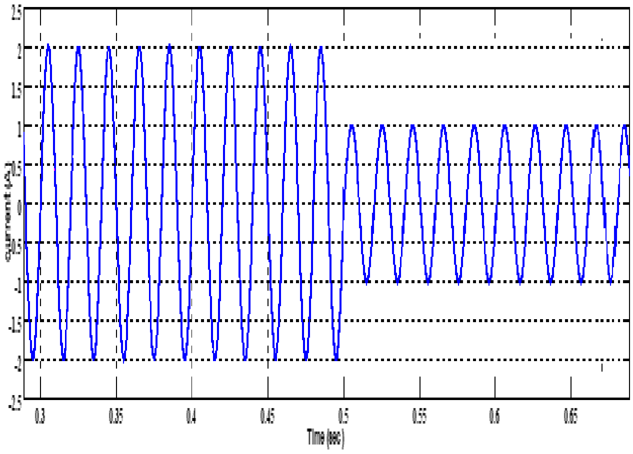


Fig.6: Simulated feeder currents under conventional control (before enabling the controller) with communication failure at t=0.5sec.

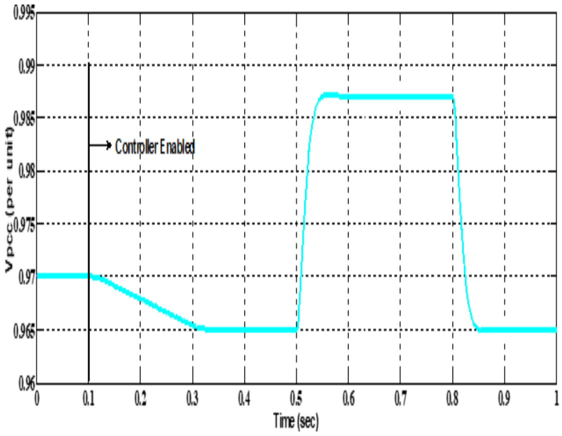


Fig.7: Performance of the MG voltage (*V*pcc) in per unit when the proposed controller is activated at *t* = 0.1 s.

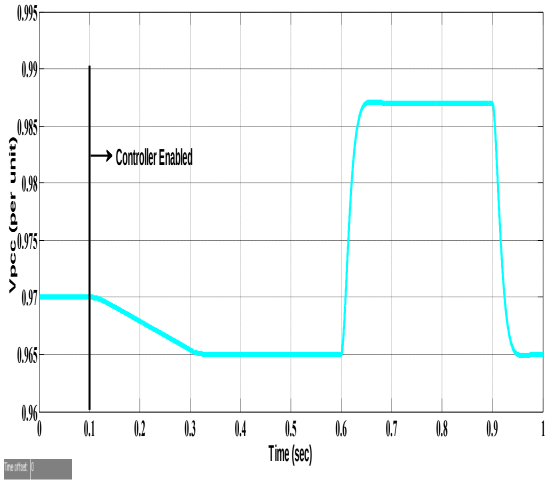


Fig.8 Behavior of the MG bus voltage (Vpcc) in per unit values when the controller Kv is enabled at t = 0.1 s. with communication failure at t=0.5sec

V. Conclusion

A market mechanism is introduced in reactive power optimization considering the reimbursable service of DG supplying reactive power and the basic framework of reactive power ancillary service market is studied in this paper to encourage decentralized generators to participate in reactive power optimization. Based on this, a reactive power optimal dispatch model in an intelligent distribution network is established in a competitive electricity market environment. Simulation results show that reactive power optimization scheduling under the reactive power ancillary service market can take into account the interests of power grid and distributed power producers. The maintenance costs of the distribution network can be reduced and the voltage level of the distribution network can be improved by considering the reactive power adjustment capability of the DG.

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