Dispatching Reactive Power Considering All Providers in Competitive Electricity Markets

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***Abstract*—This paper proposes a level playing field for the supply of reactive power ancillary services, wherein not only synchronous generators, but other providers of reactive power are also paid for their services. An Optimal Power Flow (OPF)-based reactive power dispatch model is proposed based on the reactive power payment mechanisms existent in Ontario. Novel cost models are proposed for Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) and included in the dispatch model. The proposed methodology is tested on a dispatch model of Ontario power grid, and the results show that the proposed technique can significantly reduce the cost of reactive power dispatch while maintaining system security.**

***Index Terms*- Electricity markets, reactive power dispatch, SVC, STATCOM.**

I. Nomenclature

A. Parameters

$HOEP$:	Hourly energy Ontario price in \$/MWh.
P_{Gi}:	Active power generation at bus *i* in p.u.
$Q_G^{\min}$:	Minimum reactive power limit of a generator.
P_{Di}:	Active power demand at bus *i* in p.u.
Y_{ij}:	Element of admittance matrix in p.u.
θ_{ij}:	Angle associated with Y_{ij} in radians.
Q_{Di}:	Reactive power demand at bus *i* in p.u.
$Q_{Gg}^{\min}$:	Minimum reactive power of generator *g*, in p.u.
Q_{SVC}^{rated}:	Rated VAR capacity of SVC in p.u.
$Q_{STATCOM}^{rated}$:	Rated VAR capacity of SVC in p.u.
ρ_{B1}:	Price of upward balance services in \$/MWh
ρ_{B2}:	Price of downward balance services in \$/MWh
$P_{B1i}^{\max}$:	Maximum upward balance service at bus *i* in p.u.
$P_{B2i}^{\max}$:	Maximum downward balance service at bus *i* in p.u.
$V_i^{\max}$:	Maximum allowable voltage at bus *i,* in p.u.
$V_i^{\min}$:	Minimum allowable voltage at bus *i,* in p.u.
$P_{ij}^{\max}$:	Maximum power flow from bus *i* to bus *j*, in p.u.
B_{SVC_L}	SVC minimum inductive susceptance in p.u.
B_{SVC_C}	SVC maximum capacitive susceptance in p.u.
$I_{STATCOM\_L}$	STATCOM maximum inductive current in p.u.
$I_{STATCOM\_C}$	STATCOM minimum capacitive current in p.u.
b_{SVC}:	Fixed cost component of O_{SVC}, \$/p.u.
a_{SVC}:	Variable cost component of O_{SVC} \$/p.u.

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B. Variables:

O_{SVC}:	SVC offer curve.
Q_{Gi}:	Generator reactive power at bus *i* in p.u.
P_{B1i}:	Upward balance service at bus *i* in p.u.
P_{B2i}:	Downward balance service at bus *i* in p.u.
V_i:	Bus *i* voltage magnitude in p.u.
δ_i:	Bus *i* voltage angle in radians.
P_{ij}:	Power flowing from bus *i* to bus *j*, in p.u.
δ_i:	Power flowing from bus *i* to bus *j*, in p.u.
Q_{SVC}:	SVC reactive power in p.u.
$Q_{STATCOM}$:	STATCOM reactive power in p.u.
B_{SVC}:	SVC susceptance in p.u.
$I_{STATCOM}$:	STATCOM current in p.u.
$Loss_{SVC}$:	SVC active losses in p.u.
$Loss_{STATCOM}$:	STATCOM active losses in p.u.
$Loss_{Gg}$:	Active losses in generating unit *g* in p.u.

II. Introduction

REACTIVE power dispatch is a critical short-term function carried out by power system operators in order to operate the system in a secure manner. The traditional reactive power dispatch paradigm based on minimization of losses has gradually given way to new criteria such as reactive power payment minimization [1]. In the recent literature, a two-tier structure for the management of reactive power has been proposed in the context of competitive electricity markets [2]-[4]. The latter propose that the problem of reactive power management be split into a procurement problem and a dispatch problem, with the procurement problem being essentially a long-term issue of contracting appropriate set of generators for the service provision, whereas the dispatch problem deals with allocation of reactive power generation to the units in the real-time.

In the procurement problem, the Independent System Operator (ISO) seeks to identify the generators that are critical for providing reactive power support, considering the overall system security. In [2] and [4], the problem is treated as a generator bidding process on a seasonal basis to avoid potential problems associated with the effects of price volatility of energy markets on reactive power prices. With the help of first a maximum loadability Optimal Power Flow (OPF) and then a security-constrained OPF, the ISO determines, based on reactive power offers, zonal reactive power price components and the key sets of suppliers. Once the reactive power prices are known from the procurement stage, the dispatch problem is carried out close to real-time to optimally allocate the system reactive power demand to suppliers; this process is based on an OPF that minimizes the total ISO costs associated with reactive power dispatch subject to security constraints [3], [4].

In its 1996 Order No.888, the Federal Energy Regulatory Commission (FERC) had recognized reactive power supply and voltage control services from synchronous generators as one of the six ancillary services that transmission providers must include in their open access transmission tariff. It is also stated that reactive power from capacitors and FACTS controllers, that form part of the transmission system, were *not* separate ancillary services [5]. However, there are recent recommendations from FERC to recognize reactive power provisions from sources other than synchronous generators, as ancillary services, so that they are eligible for financial reimbursement [6].

In Ontario, synchronous generators are paid for the real power losses (MW-losses) incurred when operating at non-unity power factors. Payments are made at the Hourly Ontario Electricity Price (HOEP) rates based on calculated generator losses for the hour. There is no payment for reactive capability within the standard power factor range; in other words, there is no payment in Ontario for the costs of equipment such as exciters which are deemed essential for real power production by all generators. To avoid economic distortion because of possible large revenues for generators operating solely within standard power factor ranges, capability payment for reactive power is ignored in Ontario. Alternative var suppliers such as capacitors, reactors, Static Var Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) are eligible for payments for their costs of installing and maintaining the equipment [7].

It has been discussed and demonstrated in [8] that if synchronous generators are the only reactive power ancillary service providers in the system, significant possibilities of market power can arise at certain buses in the system. It was suggested therein that in order to alleviate such situations, the reactive power market be a *level playing field* wherein all reactive power providers are considered ancillary service providers and be eligible for payment. Such a suggestion is also in line with FERC recommendations [6]. In [9], a reactive power capacity market is proposed wherein the ISO procures reactive power capacity through annual auctions; the optimal capacity is determined considering offers from generators and other sources of reactive power such as capacitors and SVCs.

In view of the above, the main objective of this paper is to propose and present a *level playing field* reactive power dispatch model that can address the problems of reactive power market inefficiencies and bring in more fairness and competition in reactive power ancillary service provisions. The proposed dispatch model seeks to minimize the ISO's total cost of reactive power dispatch, incurred through payments to the service providers, while maintaining the security of the system. It should be pointed out that, unlike [2], [3], [4] and [8], this work does not consider var price offers from the service providers, so that it is more in line with the practice of the Independent Electricity System Operator (IESO) of Ontario, which is the Control Area operator in Ontario responsible for administering the wholesale electricity market. The reactive power suppliers are paid for their active power losses (MW-losses) incurred because of reactive power provision, at the HOEP rate as in Ontario.

The approach proposed in this paper differs from that of [2]-[4] in some other aspects as well. Firstly, the procurement model is not considered here, since the framework does not require submitting price offers for reactive power. Secondly, the ISO's payment objective function has been modeled in this paper to resemble the IESO's practice, whereas in [3] and [4] the payment objective was based on reactive power dispatch and active power redispatch. Lastly, the work takes into account the presence in the dispatch model of other sources of reactive power such as capacitors, reactors, SVCs and STATCOMs, which are recognized eligible for payment for their reactive power ancillary service.

The rest of the paper is organized as follows: In Section III the cost of reactive power provision for static VAR compensators is discussed. The reactive power dispatch model is introduced in Section IV, and is based on the optimal allocation of reactive power demand to suppliers while minimizing their MW-losses, i.e. minimizing the reactive power dispatch costs for the ISO. The results from the application of the models to the IESO-controlled grid dispatch model, which is comprised of 2,833 buses and 4,205 branches, are presented and discussed in Section V. Concluding remarks and a highlight of the main contributions of the paper are provided in Section VI.

III. Cost of Reactive Power for Shunt Compensators

The dominant cost of reactive power production from shunt compensators such as SVCs and STACOMs can be decomposed into two cost components: (1) cost of installed var capacity, and (2) cost of operation. The investment cost