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The Unified Power Flow Controller Optimal Power Flow Model

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Abstract- This paper discusses the Unified Power Flow Controller (UPFC) a member of the FACTS family. UPFC is able to control both transmitted real and reactive power independently, at the sending and receiving ends of the transmission line. Also, the paper discusses UPFC modelling within the context of optimal power flow (OPF) solutions. The UPFC model is very flexible; it allows the control of active and reactive powers and voltage magnitude simultaneously. It can also be set to control one or more of these parameters in any combination or to control none of them. Considerable progress has been achieved in UPFC modelling intended for conventional load flow studies but here more complex issue of UPFC modelling intended for OPF solution is addressed.

Index Terms- FACTS, OPF, Power system, UPFC.

I. INTRODUCTION

As the load increases, power utilities are looking for ways to maximize the utilization of their existing transmission system. Continuous and fast improvement of power electronics technology has made Flexible AC Transmission System (FACTS) [1] a promising concept for power system development. By means of appropriate FACTS technology, power flow along the transmission network can be more flexibly controlled as the name implies.

Among a variety of FACTS controllers, UPFC [1] is discussed in detail. UPFC is an advanced power systems device capable of providing simultaneous control of voltage magnitude and active and reactive power flows.

UPFC was proposed for real time and dynamic compensation [2] of AC transmission systems, providing the necessary functional flexibility required to solve many of the problems facing the utility industry.

The Unified Power Flow Controller consists of two switching converters[1], which in the implementations considered are voltage sourced inverters using gate turn-off (GTO) thyristor valves (as shown in fig.1)

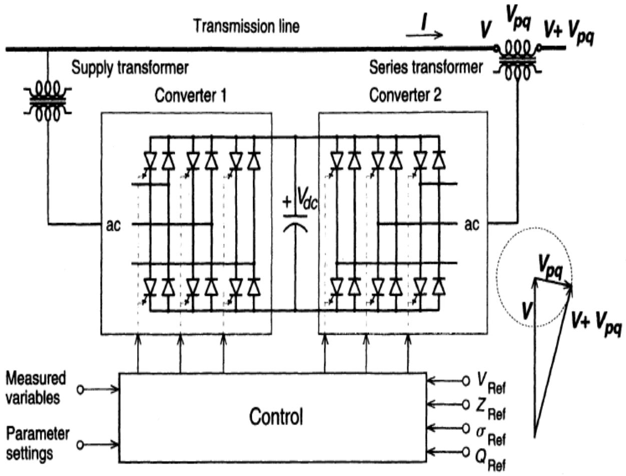

Fig.1: Basic circuit arrangement of the UPFC

These inverters labelled "Inverter 1" and "Inverter 2" in the figure are operated from a common dc link provided by a dc storage capacitor. This arrangement functions as an ideal ac to ac power converter in which the real power can freely flow in either directions between the ac terminals of two inverters and each inverter can independently generate (or absorb) reactive power at its own ac output terminals.

Inverter 2 provides the main function of UPFC by injecting an ac voltage V_{pq} with controllable magnitude V_{pq} $(0 \leq V_{pq} \leq V_{pq})$ and phase angle ρ $(0 \leq \rho \leq 2\pi)$, at the power frequency, in series with the line via an insertion transformer. This injected voltage can be considered essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. The real power exchanged at the ac terminal is converted by the inverter into dc power which appears at the dc link as positive or negative real power demand. The reactive power exchanged at the ac terminal is generated internally by the inverter.

The basic function of Inverter 1 is to supply or absorb the real power demanded by Inverter 2 at the common dc link. This dc link power is converted back to ac and coupled to the transmission line via a shunt-connected transformer. Inverter 1 can also generate or absorb controllable reactive power, if it is desired, and thereby it can provide independent shunt reactive compensation for the line. The reactive power exchanged is supplied or absorbed locally by inverter 2 and therefore it does not flow through the line. Thus, inverter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by Inverter 2. This means that there is no continuous reactive power flow through the UPFC.

When viewed the operation of the UPFC, it can perform the functions of reactive shunt compensation, series compensation and phase shifting simultaneously; thereby can meet multiple control objectives by adding the injected voltage V_{pq}, with appropriate amplitude and phase angle, to the terminal voltage, V_0.

II. UPFC IN THE SIMPLE TWO-MACHINE SYSTEM

Consider fig.2 where a simple two machine system [3] with sending - end voltage V_s, receiving - end voltage V_r, and line (or tie) impedance *X* is shown.

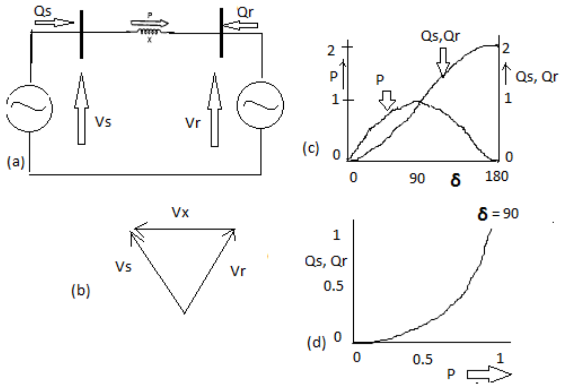

Fig.2: Simple 2-machine system (a), related voltage phasors (b), real and reactive power versus transmission angle (c), and sending-end and receiving-end reactive power versus transmitted real power(d).

Now consider fig.3 where the simple power system of fig.2 is expanded to include the UPFC. The UPFC is represented by a controllable voltage source in series[3] with the line which can generate or absorb reactive power that it negotiates with the line, but the real power it exchanges must be supplied to it, or absorbed from it, by the sending end generator.

The voltage injected by the UPFC in series with the line is represented by phasor V_{pq} having magnitude V_{pq} ($0 \leq V_{pq} \leq 0.5$p.u.) and angle ρ ($0 \leq \rho \leq 360°$) measured from the given phase position of phasor $V_{s.}$ The line current represented by phasor I, flows through the series voltage source, V_{pq}, and generally results in both real power and reactive power exchange.

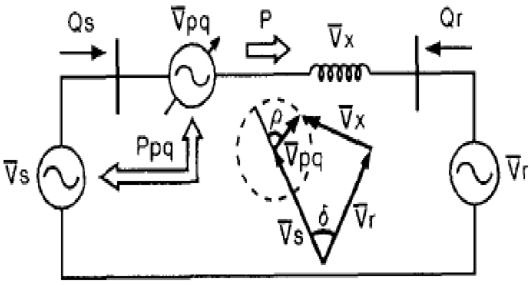

Fig.3: Two machine system with the unified power flow controller.

The real power P_{pq} is assumed to be transferred to the sending end generator. In the UPFC circuit structure, the dc link between the two inverters establishes a bi-directional coupling for real power flow between the injected series voltage source and the sending end bus. The UPFC shunt inverter is assumed to be operated at unity power factor, whose function is to transfer the real power demand to the sending end generator. With these assumptions the series voltage source, together with the real power coupling to the sending end generator is an accurate representation of the basic UPFC.

III. UPFC EQUIVALENT CIRCUITS

Two UPFC models are presented here. They are the voltage source-based model [6] and the model due to Nabavi-Niaki and Iravani [5]. These models are used as the basis of the UPFC-OPF formulation.

3.1 Voltage source – based model

The UPFC equivalent circuit shown in fig.4 [5,6] is used to derive a very flexible OPF-UPFC model[4]. The only restriction with this model is that the UPFC converter valves are taken to be lossless; Active power losses being negligible is a reasonable assumption. In this situation, the active power supplied to the shunt converter $\mathrm{Re}\{V_{VR}\ I^{*}_{\ VR}\}$ satisfies the active power demanded by the series converter $\mathrm{Re}\{V_{CR}\, I^{*}_{R}\}$.

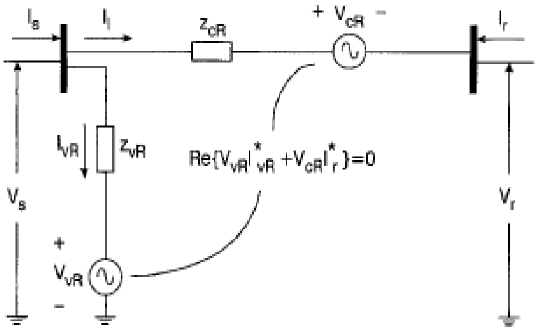

Fig.4: Equivalent source of UPFC voltage source-based model

The circuit is made up of two ideal voltage sources representing the fundamental Fourier series component of the switched voltage waveforms at the AC converter terminals. The series and shunt transformers' impedance, Z_{CR} and $Z_{VR,}$ are included in this model.

The ideal voltage sources are

$V_{VR} = V_{VR}\,(\cos\theta_{VR} + j\sin\theta_{VR})$

$V_{CR} = V_{CR}\,(\cos\theta_{CR} + j\sin\theta_{CR})$

Where V_{VR} and θ_{VR} are the controllable magnitude ($V_{VRmin} \leq V_{VR} \leq V_{VRmax}$) and angle ($0 \leq \theta_{VR} \leq 2\pi$) of the ideal voltage source representing shunt converter. The magnitude V_{CR} and angle θ_{CR} of the ideal voltage source representing the series converter are controlled between limits ($V_{CRmin} \leq V_{CR} \leq V_{CRmax}$) and ($0 \leq \theta_{CR} \leq 2\pi$) respectively.

Load flows and OPF algorithms using this UPFC model are very flexible, since the UPFC can be set to control active and reactive powers and voltage magnitude simultaneously.

3.2 Nabavi-Niaki and Iravani model

Fig.5 shows equivalent circuit representation of UPFC connected between nodes s and r, in terms of load flow terminology. This equivalent circuit is due to Nabavi-Niaki and Iravani[5].

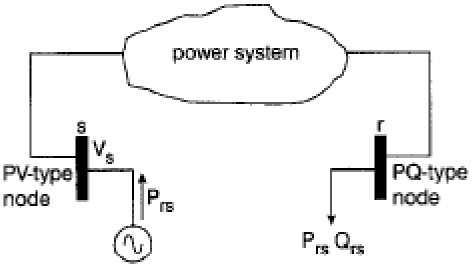

Fig.5: Nabavi-Niaki and Iravani model of UPFC

If the UPFC (converter valves and transformers) is assumed to be lossless, the UPFC can be modelled by transforming node s into a PV node and node r into a PQ-type node. This is a simple representation of the UPFC, but it will only work if nodal voltage magnitude at node s, active power flowing from nodes r to s and reactive power injected at node r, has to be controlled This model is not applicable if the limits of UPFC are violated.

IV. UPFC POWER FLOW EQUATIONS

The two UPFC models discussed above are implemented in the OPF algorithm. The active and reactive power loads at the PQ node requires no special attention within the OPF algorithm. The voltage source-based model is more flexible, and in the rest of the section voltage-source based model equations as required by the OPF algorithm are derived.

Based on equivalent circuit shown in Fig.4, the following active and reactive power equations are written:

At node s:

$P_S = V_S^2 G_{SS}$
$+ V_S V_r (G_{Sr} \cos(\theta_S - \theta_r) + B_{Sr} \sin(\theta_S - \theta_r))$
$+ V_S V_{CR} (G_{Sr.} \cos(\theta_S - \theta_{CR}) + B_{Sr.} \sin(\theta_S - \theta_{CR}))$
$+ V_S V_{VR} (G_{SR.} \cos(\theta_S - \theta_{VR}) + B_{SR.} \sin(\theta_S - \theta_{VR}))$

$Q_S = -V_S^2 B_{SS}$
$+ V_S V_r (G_{Sr} \sin(\theta_S - \theta_r) - B_{Sr} \cos(\theta_S - \theta_r))$
$+ V_S V_{CR} (G_{Sr.} \sin(\theta_S - \theta_{CR}) - B_{Sr.} \cos(\theta_S - \theta_{CR}))$
$+ V_S V_{VR} (G_{SR} \sin(\theta_S - \theta_{VR}) - B_{SR} \cos(\theta_S - \theta_{VR}))$

At node r:

$P_r = V_r^2 G_{rr}$
$+ V_S V_r (G_{rs} \cos(\theta_r - \theta_s) + B_{rs} \sin(\theta_r - \theta_s))$
$+ V_r V_{CR} (G_{rr.} \cos(\theta_r - \theta_{CR}) + B_{rr} \sin(\theta_r - \theta_{CR}))$
$Q_r = -V_r^2 B_{rr}$
$+ V_S V_r (G_{rs} \sin(\theta_r - \theta_s) - B_{rs} \cos(\theta_r - \theta_s))$
$+ V_r V_{CR} (G_{rr} \sin(\theta_r - \theta_{CR}) - B_{rr} \cos(\theta_r - \theta_{CR}))$

Series converter:

$P_{CR} = V_{CR}^2 G_{rr}$
$+ V_{CR} V_s (G_{rs} \cos(\theta_{CR} - \theta_s) + B_{sr} \sin(\theta_{CR} - \theta_s))$
$+ V_{CR} V_r (G_{rr} \cos(\theta_{CR} - \theta_r) + B_{rr} \sin(\theta_{CR} - \theta_r))$
$Q_{CR} = -V_{CR}^2 B_{rr}$
$+ V_{CR} V_s (G_{sr} \sin(\theta_{CR} - \theta_s) - B_{sr} \cos(\theta_{CR} - \theta_s))$
$+ V_{CR} V_s (G_{rr} \sin(\theta_{CR} - \theta_s) - B_{rr} \cos(\theta_{CR} - \theta_r))$

Shunt converter:

$P_{vR} = -V_{vR}^2 G_{vr}$
$+ V_{vR} V_s (G_{vR.} \cos(\theta_{vR} - \theta_s) + B_{vR} \sin(\theta_{vR} - \theta_s))$
$Q_{vR} = V_{vR}^2 B_{vR}$
$+ V_{vR} V_s (G_{vR.} \sin(\theta_{vR} - \theta_s) - B_{vR.} \cos(\theta_{vR} - \theta_s))$

Assuming a loss less converter operation, the UPFC neither absorbs nor injects active power with respect to the AC system. In this situation, the active power supplied to the shunt converter, P_{vR}, must satisfy the active power demanded by the series converter, P_{CR}. Hence,

$$P_{vR} + P_{CR} = 0.$$

V. CONCLUSION

The basics of FACTS device UPFC are discussed. Thereon, an easily understandable UPFC model intended for OPF studies is derived and UPFC power flow equations are derived. The presented model is very flexible; it takes into account various UPFC operating modes. Although the Nabavi – Niaki and Iravani model has some disadvantages, it gives rise to more complex equations.

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