Power Control of Ann based of Series Converter of Unified Power-Flow Controller with Three-Level Neutral Point Clamped Converter

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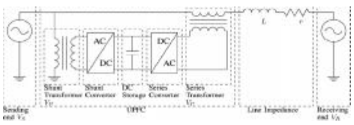
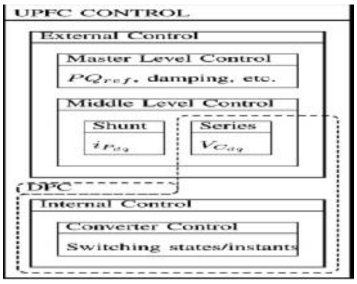
Abstract*—A unified power-flow controller(UPFC) can enforce unnatural power flows in a transmission grid, to maximize the power flow while maintaining stability. Theoretically, active and reactive power flow can be controlled without overshoot or cross coupling. This paper develops ANN power control, based on instantaneous power theory, to apply the full potential of converter. Simulation and experimental results of a full three-phase model with non ideal transformers, series multilevel converter, and load confirm minimal control delay, No overshoot nor cross coupling. A comparison with other controllers demonstrates better response underbalanced and unbalanced conditions. Direct power control is a valuable control technique for a UPFC, and the presented controller can be used with any topology of voltage-source converters. In this paper, the direct power control is demonstrated in detail for a third-level neutral point clamped converter .Index Terms—ANN ower control, flexible ac transmission control(FACTS), multilevel converter, sliding mode control, unified power-flow controller (UPFC).

I. INTRODUCTION



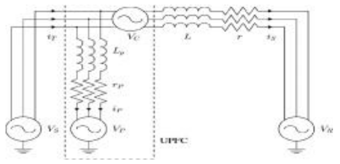
One-wire schematic of the transmission line with UPFC.

Operator A unified power-flow controller (UPFC) is the most versatile of these FACTS devices. A transmission line equipped with a UPFC can control the balance of the transmitted power between parallel lines and, as such, can optimize the use of the transmission grid for all parallel power flows. A one-wire schematic of a transmission-line system equipped with a UPFC is given in Fig. 1. A UPFC is connected to the transmission line by coupling transformers, both with a shunt and with a series connection. The UPFC consists of two ac/dc converters, the ac sides connected to the shunt and series connection with the transmission line, and the dc sides connected back to back. UPFCs are typically built with voltage-sourced converters, having a capacitor as (limited) dc energy storage. In Fig. 2, an overview of the most common control structure for UPFCs is displayed. An external control describes the set points of the power system (steady state or dynamic). The internal control describes the actual power electronics and safeties of the UPFC , The external control is typically divided into a master and middle control . The master control handle stargets such as an optimal power system setpoint, increase of transient stability, or subsynchronous resonance dampening and delivers the middle control setpoints. Middle control translates these master setpoints into setpoints for the series and shuntconverter. The series and shunt controller can have, but do not require , internal communication for stability increase or optimization. The internal controller translates these middle-level control setpoints into switching decisions for the power-electronic components. Higher level control techniques have primarily focussedon optimizing power flow . Later on, the focus shifted to damping sub synchronous resonances of turbine generator shafts and inter area oscillations and transient stability increase . Various methods are used to switch intelligently



UPFC controller classification according to and the position of the proposed direct power controller (DPC).

between higher level control priorities Recently, a lot of interest into the increase of grid reliability is shown The first designs of middle-level power-flow controllers for UPFC used direct control which suffered from serious crossc-oupling . Decoupling control improved this cross-coupling,with high sensitivity to system parameter knowledge, and cross-coupling control of direct and quadrature series-injected voltages to active and reactive power improvedon that. Cross-coupling control with direct control oscillationdamping enhanced performance ,but basedon PIcontrolstructures, realized a low control bandwidth , . The instantaneous power conce enabled faster controltechniques, putting, however, a larger strain on the computationalcapacity of the controllers . The controllerproposed in this paper combines two control levels—themiddle-level series converter control and internal convertercontrol—thereby increasing the simplicity of the controller andincreasing the control dynamics. Since the series converter istypically used for power-flow control, the controller realizes adirect relation between the desired power flow and switchingstates, and is therefore named a ann power controller the precise location of the proposed ann is displayed.The ann power controltechnique used in this paper findsits design principles in instantaneous power theory and sliding mode control . Relying on these two techniques, a sliding surface is defined in function of the instantaneous active and reactive power, and the system is controlledto stay on the surface. A similar controller was developed for amatrix converter . This paper is a follow up paper to ,with a more detailed explanation of the controller design and acomparison to other controllers.The series and shunt converter of a UPFC are HV powerelectronics. To minimize the voltage stress on all componentswhile increasing the system voltage level, multilevel neutralpoint clamped inverters are a promising topology. The ANN PCcontrolmethod described in this paper is divided in two parts—a



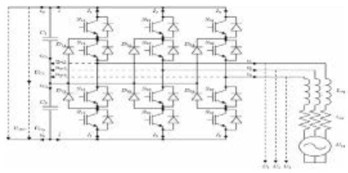
Schematic of the equivalent circuit of the UPFC system.

general external part and an internal topology-specific part. Thedesign principles for both are explained in detail. The externalpart is universal, the internal part can easily be adapted to differenttopologies of voltage-source converters. In this paper, athree-level neutral point clamped converter is used. Other convertertopologies use the converter independent partwithout furthertheoretical development

II. UPFC SERIES CONVERTER MODEL

During model construction and controller design, powersources , are assumed to be infinite bus. We assume seriestransformer inductance and resistance negligible comparedto transmission-line impedance. Connection transformers ofseries and shunt converters of the UPFC as in Fig. 1 are not explicitlyincluded in the mathematical model used for controllerdesign. Under these assumptions, we can simplify the grid asexperienced by the UPFC to Fig. 3. Sending and receiving endpower sources , are connected by transmission line , .The total current drawn from the sending end consists of thecurrent flowing through the line and the current exchangedwith the shunt converter . Shunt transformer inductance andresistance are represented by and . The series inductanceand resistance are commonly accepted as a model for overheadtransmission lines of lengths up to 80 km .The power to be controlled is the sending end power, formedby the current and the sending end voltage . This is themost realistic implementation for control purposes.The UPFC shunt converter model is similar and is not describedin this paper; its functions and control are well describedin literature and the performance of the shunt converteris only of secondary influence on the control system describedin this paper, as demonstrated in previous work .Effects of dc bus dynamics are negligible in the control bandwidthof the power flow. For all simulations and experimentsin this paper, the shunt converter is

III. THREE-LEVEL NEUTRAL POINT CLAMPED CONVERTER



Schematic of the three-level neutral point clamped converter.

A schematic of a three-level neutral point clamped converteris given in Fig. 4. This topology and its mathematical modelhave been diligently described in . Each leg of the converterconsists of four switching components and two diodesThe diodes , clampthe voltages of the connections between , , and , ,respectively, to the neutral point, between capacitors , .There are three possible switching combinations for each leg thus three voltages . The three levels for voltagesproduce five different converter phase-output voltages . Theupper and lower leg currents , or their respective sum ,can bedescribed in function of the output line currents . Thesystem state variables are the line currents , , , and the capacitorvoltages , . This system has the dc-bus currentand the equivalent load source voltages as inputs.Under the assumption that the converter output voltages areconnected to an , system with a sinusoidal voltage sourcewith isolated neutral, as in Fig. 4, we can write the equationsfor the three-phase currents

$L_{eq} \cdot \frac{di_k}{dt} = U_k - r_{eq} \cdot i_k - U_{eqk}$ The capacitor voltages U_{C_1}, U_{C_2}, are influenced by the sum ofthe upper and lower leg currents , and the input current ,as in $\frac{dU_{C_1}}{dt} = \frac{i_{C_1}}{C_1} = \frac{i_0 + i}{C_1}$, $\frac{dU_{C_2}}{dt} = \frac{i_{C_2}}{C_2} = \frac{i_0 + i}{C_2}$ From the restrictions on the states of the switching devices ineach leg of the converter, we can define the ternary variable $\gamma_k(t)$, representing the switching state of the entire leg, as

$$\gamma_k(t) = \begin{cases} (S_{k1}, S_{k2} = \text{on}) \wedge (S_{k3}, S_{k4} = \text{off}) & \rightarrow 1 \\ (S_{k2}, S_{k3} = \text{on}) \wedge (S_{k1}, S_{k4} = \text{off}) & \rightarrow 0 \\ (S_{k3}, S_{k4} = \text{on}) \wedge (S_{k1}, S_{k2} = \text{off}) & \rightarrow -1. \end{cases}$$

To simplify notation, combinations of this variable , and are introduced

$$\Gamma_{1k} = \frac{\gamma_k}{2} \cdot (1 + \gamma_k)$$
$$\Gamma_{2k} = \frac{\gamma_k}{2} \cdot (1 - \gamma_k)$$
$$\Gamma_1 = [\Gamma_{11} \quad \Gamma_{12} \quad \Gamma_{13}]$$
$$\Gamma_2 = [\Gamma_{21} \quad \Gamma_{22} \quad \Gamma_{23}]$$
$$\Xi = \frac{1}{3} \cdot \begin{bmatrix} 2 \cdot \Gamma_{11} - \Gamma_{12} - \Gamma_{13} & 2 \cdot \Gamma_{21} - \Gamma_{22} - \Gamma_{23} \\ -\Gamma_{11} + 2 \cdot \Gamma_{12} - \Gamma_{13} & -\Gamma_{21} + 2 \cdot \Gamma_{22} - \Gamma_{23} \\ -\Gamma_{11} - \Gamma_{12} + 2 \cdot \Gamma_{13} & -\Gamma_{21} - \Gamma_{22} + 2 \cdot \Gamma_{23} \end{bmatrix}$$

where , $\Xi(\gamma_{123}), \Gamma_1(\gamma_{123}), \Gamma_2(\gamma_{123})$
, are aiding functions describing the precise
dynamics in function of the switching state. It is important to

realize that this system equation is not constant, nor continuous

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ U_{C_1} \\ U_{C_2} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_{eq}} \cdot I_3 & \frac{\Xi(\gamma_{123})}{L_{eq}} \\ -\frac{\Gamma_1(\gamma_{123})}{C_1} & 0_{1,2} \\ -\frac{\Gamma_2(\gamma_{123})}{C_2} & 0_{1,2} \end{bmatrix} \cdot \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ U_{C_1} \\ U_{C_2} \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_{eq}} \cdot I_3 & 0_{3,1} \\ 0_{1,3} & \frac{1}{C_1} \\ 0_{1,3} & \frac{1}{C_2} \end{bmatrix} \cdot \begin{bmatrix} U_{eq1} \\ U_{eq2} \\ U_{eq3} \\ i_0 \end{bmatrix}$$

Vector	γ_1	γ_2	γ_3	$C \cdot d(U_{C_1} - U_{C_2})/dt$	$\gamma_{123} \cdot i_{123}$
1	1	1	1	0	0
2	1	1	0	$-i_1 - i_2$	$i_1 + i_2$
3	1	1	−1	0	$2 \cdot (i_1 + i_2)$
4	1	0	−1	i_2	$2 \cdot i_1 + i_2$
5	1	0	0	$-i_1$	i_1
6	1	0	1	i_2	$-i_2$
7	1	−1	1	0	$-2 \cdot i_2$
8	1	−1	0	$-i_1 - i_2$	$i_1 - i_2$
9	1	−1	−1	0	$2 \cdot i_1$
10	0	−1	−1	i_1	i_1
11	0	−1	0	$-i_2$	$-i_2$
12	0	−1	1	i_1	$-i_1 - 2 \cdot i_2$
13	0	0	1	$i_1 + i_2$	$-i_1 - i_2$
14	0	0	0	0	0
15	0	0	−1	$i_1 + i_2$	$i_1 + i_2$
16	0	1	−1	i_1	$i_1 + 2 \cdot i_2$
17	0	1	0	$-i_2$	i_2
18	0	1	1	i_1	$-i_1$
19	−1	1	1	0	$-2 \cdot i_1$
20	−1	1	0	$-i_1 - i_2$	$-i_1 + i_2$
21	−1	1	−1	0	$2 \cdot i_2$
22	−1	0	−1	i_2	i_2
23	−1	0	0	$-i_1$	$-i_1$
24	−1	0	1	i_2	$-2 \cdot i_1 - i_2$
25	−1	−1	1	0	$-2 \cdot (i_1 + i_2)$
26	−1	−1	0	$-i_1 - i_2$	$-i_1 - i_2$
27	−1	−1	−1	0	0

OUTPUT VOLTAGE VECTORS

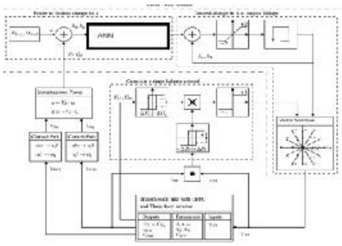
IV ANN POWER CONTROL Artificial Neural Networks are relatively crude electronic models based on the neural structure of the brain. The brain basically learns from experience. It is natural proof that are beyond the scope of current computers are indeed solvable by small energy efficient packages. This brain modeling also promises a less technical way to develop machine solutions. These biologically inspired methods of computing are thought to be the next major advancement in the computing industry. Even simple animal brains are capable of functions that are currently impossible for computers. Computers do rote things well, like keeping ledgers or performing complex math. But computers have trouble recognizing even simple patterns much less generalizing those patterns of the past into action of the future.

Now, advance in biological research promise an initial understanding of the natural thinking mechanism. This research shows that brain stores information, as patterns. Some of these patterns are very complicated and allow us the ability to recognize individual faces from any different angles. This process of storing information as patterns, utilizing those patterns, and then solving problems encompasses a new field in computing. This field does not utilize traditional programming but involves the creation of massively parallel networks and the training of those networks to solve specific problems. This field also utilizes words very different from traditional computing, words like behave, react, self-organize, learn, generalize, and forgot. An artificial neural network (ANN), often just called a "neural network" (NN), is a mathematical model or computational model based on biological neural networks. It consists of an interconnected group of artificial neurons and processes information using a connectionist approach to computation. In most cases an ANN is an adaptive system that changes its structure based on external or internal information that flows through the network during the learning phase. In more practical terms neural networks are non-linear statistical data modeling tools. They can be used to model complex relationships between inputs and outputs or to find patterns in data. A neural network is an interconnected group of nodes, akin to the vast network of neurons in the human brain.

PRINCIPLE OF OPERATION

In the selection *Power to desired change in* of Fig. 6, theimplementation of 19 exists. To select a physical voltagevector, this decision process is transformed to the domain,remaining with requested changes of the UPFC seriesoutput voltage in to the output voltage vector. To limit theswitching frequency, the decision is suppressed until the systemstate crosses a parallel surface at a certain distance from the directpower control surfaces . Note that this requested changeis not expressed in a numeric value of the requested change,but as the direction of change (in this case, a ternary variable,indicating increase , no change 0, decrease). Dependingon the currently used output vector and the requested change in, an appropriate next vector can be selected. This concludesthe converter topology independent part of the controller.

In Fig. 6, in the selection *Desired change in to outputVoltage*, for a three-level NPC converter, the voltage vectorselection is displayed. DPC demands increasing or decreasingthe output voltage vector in the and direction. Based on
the currently applied vector and this demand, the next vectoris selected. This is simplified to selection of the voltage vector
levels , . In the cases that vectors coincide, an extracriterium is needed to unambiguously select a set of switching



Overview of the control algorithm.

IT CAN BE CONTROL TWO CONDITION

A. DPC Simulation and Experiment in Balanced Conditions

Both in simulation and in experiment, , take values
of 0 to 0.316 p.u. and change stepwise. It should be noted that thereferences , do not represent a realistic reference profile.An overview of 2.5 s of the closed-loop controlled output in

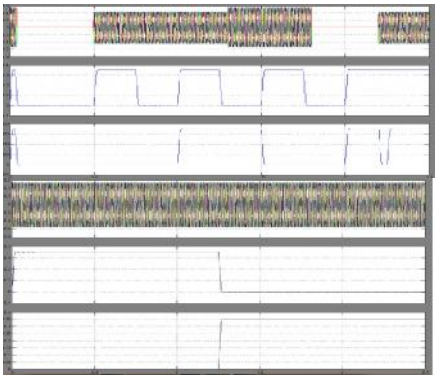
TABLE IV

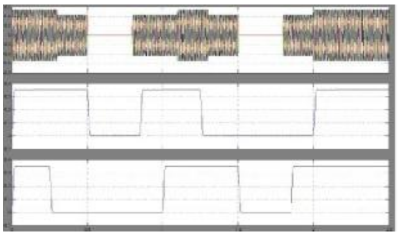
CONTROLLER PARAMETERS

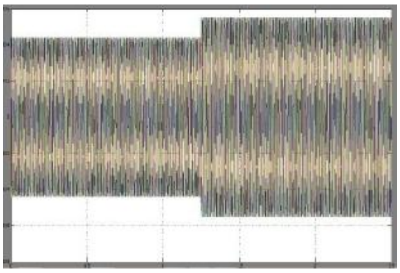
Figs, demonstrates that the system can handle any combinationof sending end power references , , and referencechanges , . A more detailed look at the results shows that there are no low-frequency phenomenain the currents, and that they are balanced. The directpower controlled system demonstrates no overshoot, no crosscoupling, no steady-state error, and a fast rising and settlingtime.

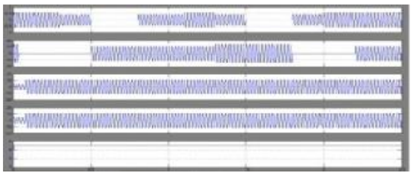
B. DPC Compared to Other Controllers

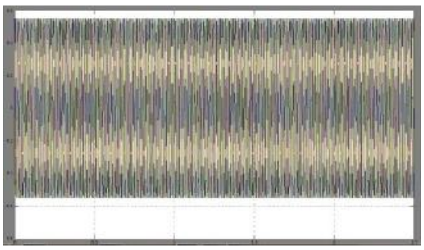
The same simulation model is used as in the previous test.The DPCwill be compared with two other controllers: advanced
dynamic control (ADC) and dynamic inverse control (DIC) Both are middle-level controllers, with a clearly described

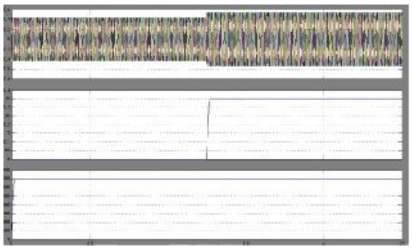












RESULTS

The discussed controller is demonstrated in simulation andin experimental results. Fig. 7 shows the experimental setup.A DSpace controller board is used. For controlled startup andease of use, an autotransformer is used to regulate the mainsvoltage on the setup. Two isolation transformers are connectedto the autotransformer, to represent the sending and receivingend voltages , . Iron cored coils are used to represent theload impedance , and transmission-line impedances „ and , . Another step down isolation transformer is usedfor the series connection of the UPFC inverter to the grid. Thevalues of the separate components are given in Appendix A.Both the simulation and experimental setups use these parametervalues so that results can be compared.The simulation is based on a full three-phase model of theUPFC and the power lines constructed with Matlab Simulink. Itis performed on a balanced model of the experimental setup. Itcontains a model of the converter based on the dynamic equationsand control laws as described in Section IV. UPFC shuntconverter and dc capacitor dynamics are included in the system

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