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Sizing Study for a Hybrid Power Flow Controller – Comparison with the Nanjing UPFC

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SUMMARY

The Nanjing UPFC is the world's first UPFC based on a modular multilevel converter (MMC). It was recently installed on the Tiebei-Xiaozhuang transmission corridor to increase the available transfer capacity of the Xiaozhuang transmission interface into the Nanjing Western Power Grid. The MMC technology developed for this application enables a streamlined deployment of any converter-based FACTS configuration. In this paper, we explore applying a Hybrid Power Flow Controller (HPFC) in the same system environment. An HPFC is a symmetrical device. In the studied configuration it uses a shunt-connected source of reactive power and two series-coupled converters, one on each side of the shunt device.
The paper begins by describing the change in system flows achieved by the incumbent UPFC. This is followed by presenting a method that defines the desired operating point for a compensator without pre-selecting the compensator type. This enables a system-centric approach to compensator selection and allows for merit-based comparison of several candidate FACTS technologies. This method is then used to select an HPFC that achieves the same increase in power flow through the Tiebei-Xiaozhuang double circuit line as is achieved by the incumbent UPFC. Optimizing the ratings of the HPFC requires slight modifications to reactive exchanges at the compensator terminals; we calculate and tabulate these differences to allow for full comparison. The changes are insignificant relative to the capital expenditure (CAPEX) savings realized by replacing the shunt converter of the UPFC with a switched shunt capacitance in the HPFC.
Next, the paper explores further modifying the system operating point to eliminate the loop flow. Both UPFC and HPFC can be configured to achieve this, but the resulting operating point of a compensator requires increase in shunt and reduction in series device ratings. This is a favorable change for an HPFC, because its shunt device is based on a switched capacitance, but unfavorable for a UPFC, because it gets in the way of operational flexibility and partial functionality with a loss of one converter—the ratings of the incumbent UPFC were optimized to use three equally rated converters.

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The paper concludes by reviewing economic benefits afforded by the considered options, using illustrative equipment capital costs and illustrative differences in locational marginal price of energy on the two sides of the Xiaozhuang transmission interface. The compensators are compared based on a ten-year net present value assuming a capacity factor of 40%. The analysis shows the payback period can be as low as 9 months.
The findings are promising for converter-based FACTS controllers. Using MMC technology enables optimizing FACTS device topology to suit the needs of the application using the same equipment building blocks. This allows for deployment of FACTS solutions at a reduced technical risk, making the selection of a FACTS compensator an application engineering choice, not a technology one. Furthermore, this allows for standardization of equipment specifications, allowing market participation by many vendors and promising to make converter-based FACTS controllers significantly more cost-effective.

KEYWORDS

Converter-based FACTS compensators, Hybrid Power Flow Controller (HPFC), Unified Power Flow Controller (UPFC), Modular Multilevel Converter (MMC)

INTRODUCTION

The world's first modular multi-level converter (MMC) based Unified Power Flow Controller (UPFC) was put in operation in December of 2015 in Nanjing China [1]. It solves the problem of balancing supply to the power grid of western Nanjing shown in Figure 1.

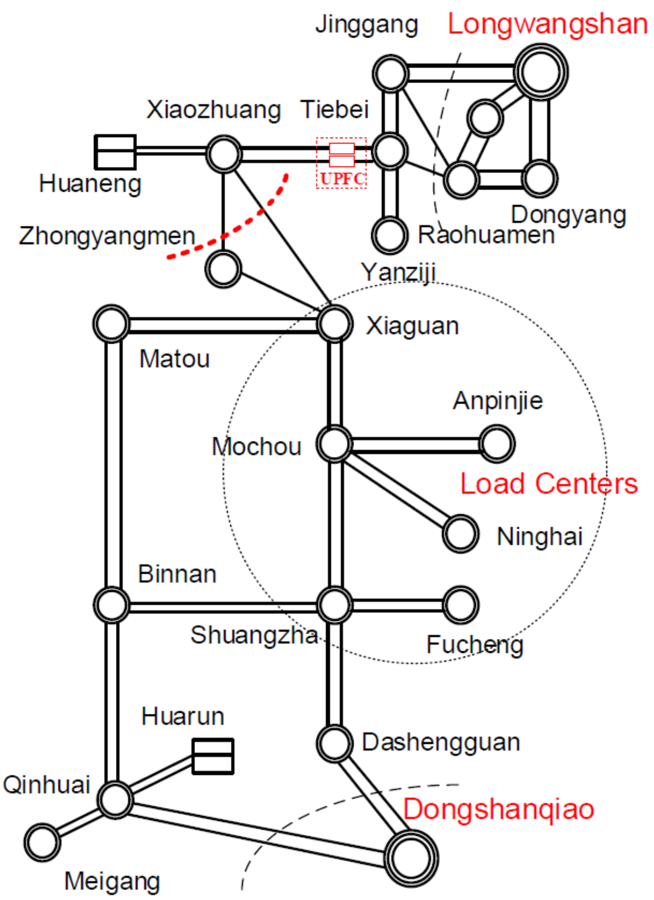

Figure 1 Nanjing western grid

Referring to the figure, power to the city is supplied from the 500kV system via Longwangshan substation in the north, and Dongshanqiao substation in the south. The triple concentric circles used to label these substations designate their 500kV voltage level, all other buses are labelled by double concentric circles to designate the 220kV voltage level.

The UPFC is installed on the double circuit 220kV line between the Tiebei and Xiaozhuang substation and is used to control the flow of power into the city from the northern corridor. This overcomes the problem of power flow into the city being a function of prevailing flows on the 500kV system and the 220kV portion of the system being a parallel path to the 500kV system. Rather, the flows through the 220kV system can now be made independent of angular difference between Longwangshan and Dongshaqiao buses, which enables better utilization of 220kV system and supports the city's future load growth without developing additional transmission [2].

The system in Figure 1 is further simplified in Figure 2 to facilitate the discussion of choosing the type and ratings of a suitable compensator to achieve the system objectives. Referring to Figure 2, the sending area of the system (the portion of the system between the Tiebei and Longwangshan substations) is represented by the Thévenin's equivalent impedance Zs, and the Thévenin's equivalent voltage at the Longwangshan 500kV system by Us. Analogously, the portion of the system between the Xiaozhuang and Dongshanqiao substations is represented by the Thévenin's equivalent impedance Zr and the Thévenin's equivalent voltage at the Dongshanqiao 500kV system by Ur. The compensator is installed at the sending side of the double–circuit line, between the buses U1 and U2, representing the internal buses of the Tiebei substation. The double–circuit line is shown as two parallel reactances, labeled XL, connecting the buses U2 and U3. Bus U3 represents the Xiaozhuang substation. There is a parallel path through the system between the buses U1 and U3 represented by the series connection of Rm and Xm.

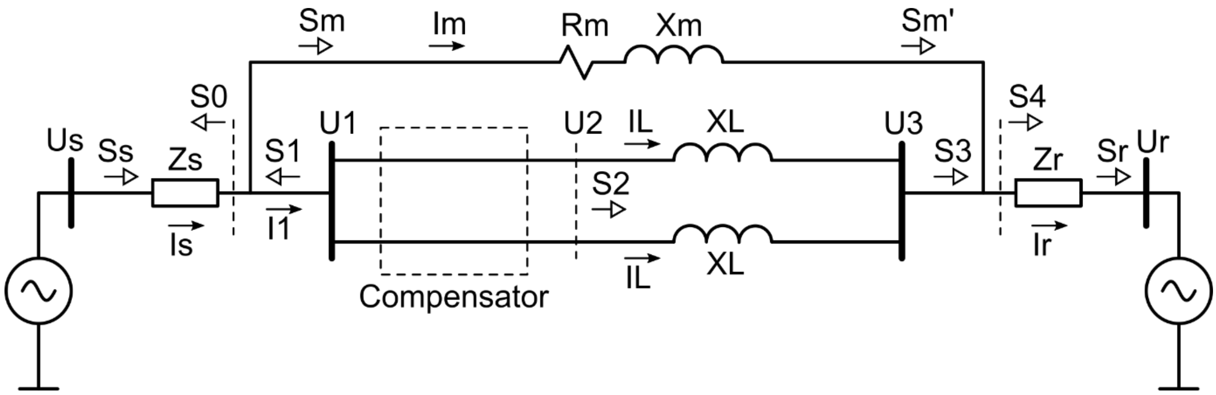

Figure 2 System configuration before compensation

The values of circuit parameters, magnitudes and angles of voltage phasors Us and Ur, and the apparent powers at the key points in the system before and after the compensation are documented in Appendix A. Figure 2 also documents the reference directions for currents and apparent powers in the system used in this paper.

The baseline system was compensated by a unified power flow controller (UPFC) that increased the power flow through the double circuit line from S2 = 701.8MW+j154.4MVAr to S2 = 900MW + j200MVAr.

The objective of this paper is to select the ratings of a Hybrid Power Flow Controller (HPFC) [3] that can replace the incumbent UPFC and achieve the same increase in power flow on the double circuit line.

COMPENSATION OPTIONS

System Compensated by a UPFC

The configuration of a reference UPFC is shown in Figure 3. To achieve operational flexibility and enable partial functionality with a loss of one converter, the UPFC was designed to use three equally rated converters: one in shunt and two in series. Within the context of this analysis, the two series converters operate at identical operating points, so they are considered as one converter with the apparent power of 2 Sser. The UPFC operating point can be uniquely specified by the set of system variables with values summarized in Table 1.

Table 1 Specified UPFC operating point

Apparent Power	MW	MVAr
S1	-903.4	-107.1
S2	900.0	200.0
Qsh		30.0

It follows that the total UPFC losses are Re(−S1−S2) = 3.4MW. Since the HPFC uses fewer converters than the UPFC, its converter–related losses will be significantly smaller, making it more appropriate to compare the two compensators on the basis of lossless converters.

Consequently the specified value of S1 was adjusted to set the converters' losses to zero, yielding: S1 = −900.0MW − j107.1MVAr.

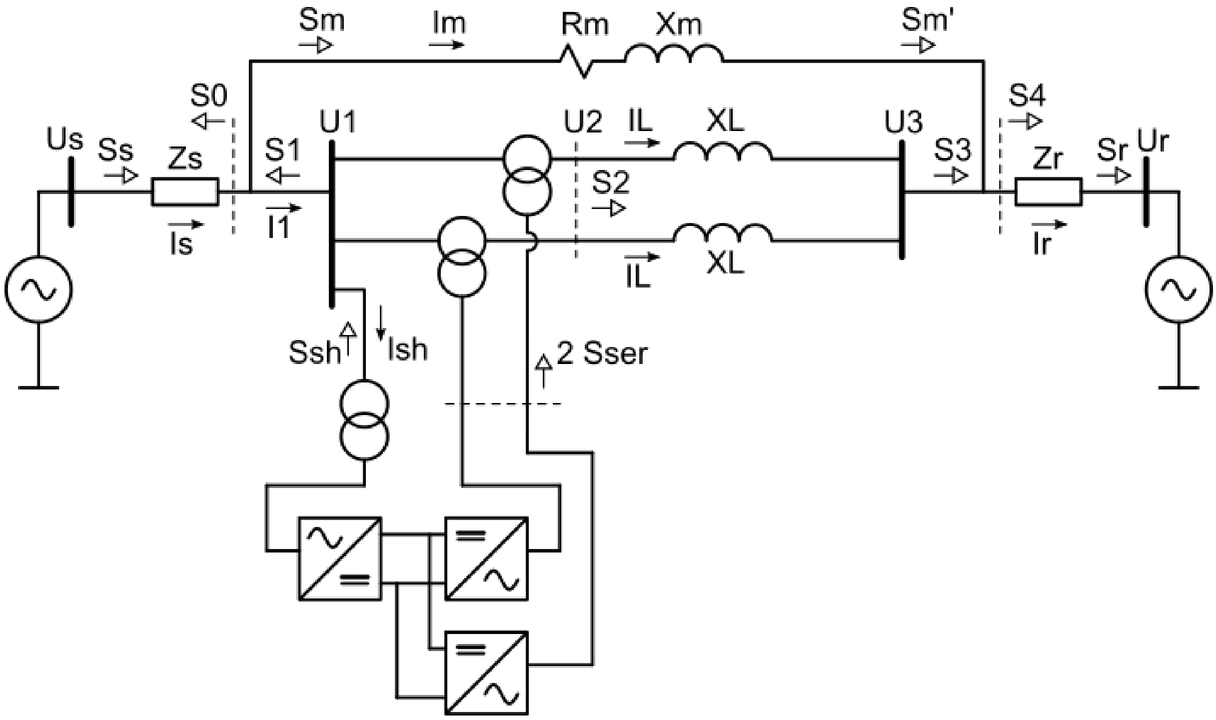

Figure 3 System compensated by a UPFC

Using the adjusted value for S1 with the specified values for S0, S3, S4, and voltages Us and Ur (all provided in Appendix A), yields the unique solutions for the UPFC converters' operating points. These solutions are listed in Table 2.

Table 2 Solved operating points of the UPFC converters

Apparent Power	MW	MVAr
Ssh	8.03	30.1
2 Sser	-8.03	62.8

System compensated by an HPFC

The system compensated by an HPFC is shown in Figure 4. The HPFC uses a shunt–connected source of reactive power and two series converters, one on each side of the shunt device.

As in the UPFC, the converters of an HPFC share the DC bus and can exchange active power. This provides the HPFC with the same operational degrees of freedom as those of the UPFC. To understand this, consider both compensators as black boxes with two sets of terminals: the input at U1, and the output at U2. Without prescribing the content of the black box, four degrees of freedom can be identified: Two come from independently adjustable magnitude and angle of U1, and another two from magnitude and angle of U2. There is also one constraint: The active power delivered at the output (plus any compensator's losses) must be matched by the active power extracted from the input. Respecting the constraint requires sacrificing one degree of freedom, so the remaining number of operational degrees of freedom is three.

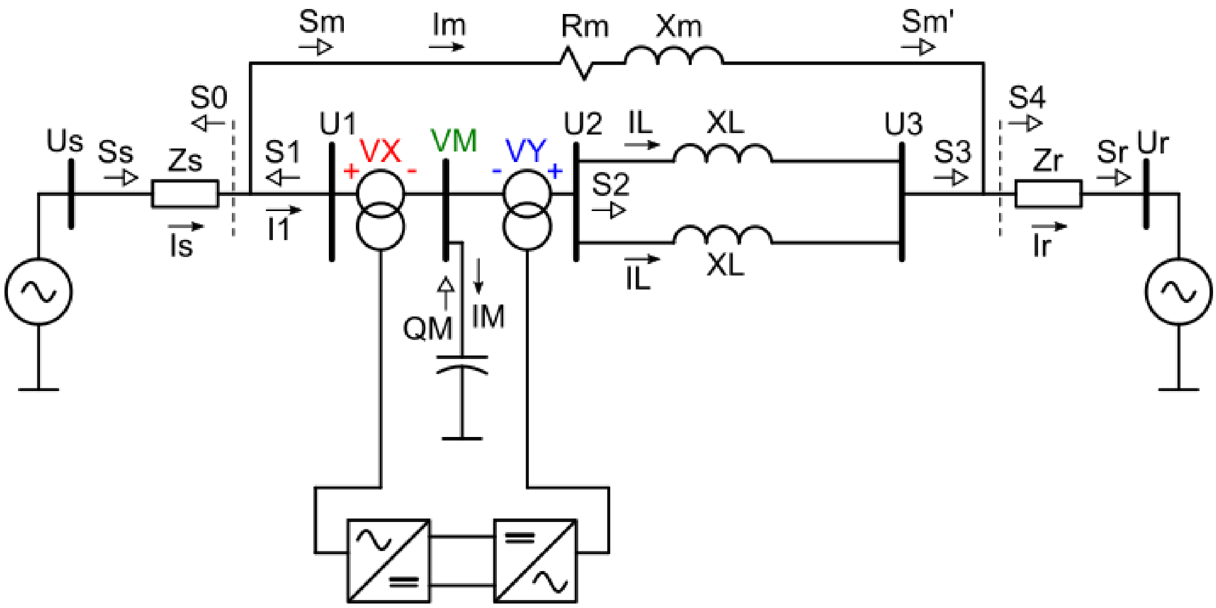

Figure 4 System Compensated by an HPFC

To simplify considerations of such two–terminal compensators in power system analysis, it is helpful to represent their operating points by variables commonly used to represent generators. Generators are represented by either their active and reactive power contributions to the system, or by their active power contributions and the voltage magnitudes at their terminals. For the purpose of this analysis, the operating point of the two-terminal compensator will be specified by providing commands for P2, Q1, and Q2, referred to here as the PQQ commands. Specifying PQQ commands retains the three available degrees of freedom for selecting the compensator's operating point and avoids two major downsides of using terminal voltages as control inputs:

1) A power system operating in real time has no absolute reference for voltage angle; voltage magnitudes and angles are dependent on continuously changing load and generation levels, and are thus changing all the time. As a result, voltage commands would have to be given relative to angles of other busses in the system and considering the prevailing power flows, which would require high–speed measurements of many remote variables in real time.
2) The active power constraint cannot be enforced by simply stipulating a relationship between voltages U1 and U2. This is because the apparent power flows out–of and in–to the compensator also depend on the operating point of the hosting power system and are a function of continuously changing load and generation levels.

Operating a compensator using PQQ commands solves both of these problems. Specifically, for each PQQ command given in the context of an operating point of the hosting power system, there exists a unique solution for voltages U1 and U2 that is guaranteed to respect the active power constraint. The added benefit is that this holds true for any two-terminal compensator, and thus enables an efficient comparison between various compensator options; in this case between the reference UPFC and its candidate replacement HPFC.
In the next section, a set of ratings for the HPFC is chosen to achieve the PQQ flows through the system similar to those achieved by the UPFC, but such that the series converters' ratings of the HPFC are minimized to optimize the capital cost for a replacement HPFC.

SIZING THE HPFC

As was discussed in the previous section, an operating point of a compensator within the power system is specified by the PQQ commands. To achieve uniqueness in specification of the operating point of the compensated system, the specification for the operating point of the hosting power system must be added to the compensator's PQQ commands. The specification given in Appendix A, achieves this by defining the circuit parameters and the magnitudes and angles of Thévenin's equivalent voltages: Us and Ur.

The solved voltage vectors of the system compensated by the UPFC are shown in Figure 5. The system voltages Us, U3, and Ur are represented by the (unlabelled) black vectors. Angles of voltages Us and Ur are as specified by NR Electric: 18.8° and 0° electrical, respectively. The vector U3 is between Us and Ur, and its magnitude and angle relative to Ur are such that it drives the increased power flow across the impedance Zr. The UPFC voltages are shown in terms of converter voltages: Vsh is the voltage defined by the shunt converter and it is identical to the system voltage U1. Voltage U2 is shown indirectly and is defined as U2 = Vsh + Vser, so the tip of Vser corresponds to the tip of U2.

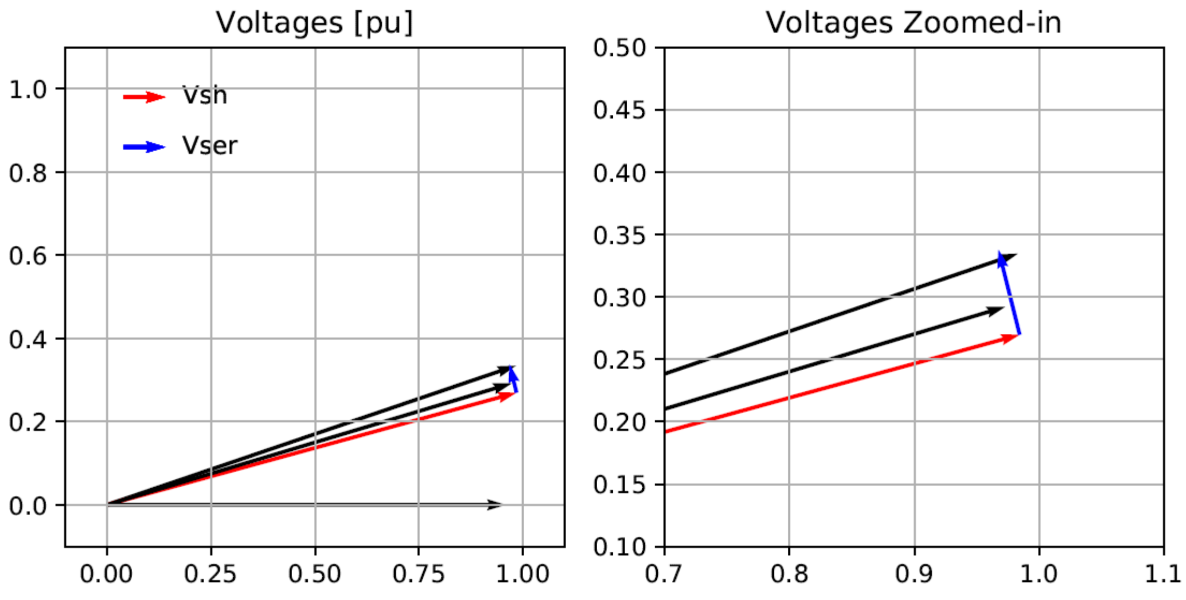

Figure 5 System compensated by a UPFC (Case code 02)

The corresponding operating point of a functionally equivalent HPFC is shown in Figure 6. The system operating point corresponds to the one shown in Figure 5 represented by the solutions of system voltage vectors: Us, U1, U2, U3, and Ur. As was the case in Figure 5, vectors Us, U3, and Ur are shown in black (with no labels,) while the vectors U1 and U2 are shown indirectly: The tip of U1 corresponds to the tip of VX and the tip of U2 corresponds to the tip of VY. (For labels and reference directions of voltages within the HPFC, refer to Figure 4.)

Additional reductions in the HPFC's converters' ratings can be achieved by relaxing the constraint of Us angle. Careful inspection of the operating points shown in Figures 4 to 6 shows that U3 leads relative to U1, causing the loop flow in the electromagnetic parallel path. The loop flow can be eliminated by allowing the generators in the sending area to advance by 4.7° electrical and dispatching the compensator to achieve the target flow through the double circuit line, while maintaining the pre-compensation flow through the parallel path. The operating points corresponding to these conditions were solved under the case codes: 22 for a UPFC and 25 for an HPFC. The corresponding equipment ratings for all equipment options are summarized in Table 3.

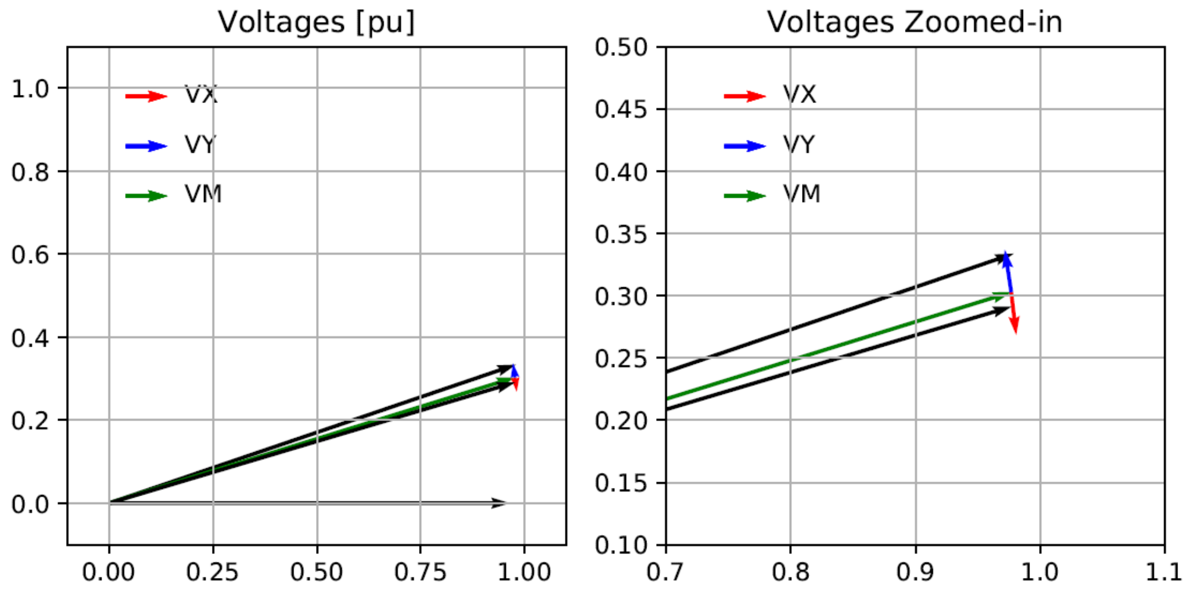

Figure 6 System compensated by an HPFC (Case code 05)

Table 3 Comparison of equipment ratings for select system operating points

Case code	Compensator	|Ssh|	Qsh	Σ |Sser|
02	UPFC	31.2	n/a	63.3
05	HPFC	n/a	31.2	61.7
22	UPFC	83.6	n/a	9.6
25	HPFC	n/a	83.7	9.2

The modified operating point results in increased contribution of reactive power from the shunt device, and reduced MVA contributions from the series converters. While the MVA contributions by the shunt and series branches of the two compensators are approximately equivalent, the HPFC has a significantly lower capital cost because of its ability to deploy a passive device in its shunt branch.

COST BENEFIT ANALYSIS

The equipment ratings from Table 3 can be mapped into capital expenditures and considered as an investment that achieves savings in system operation over time. While every application scenario will be different in terms of savings, we present an example cost benefit analysis using representative assumptions about equipment capital costs, system operating profile using the capacity factor as its proxy, and a price differential in value of energy in the southern and northern part of the system. The assumptions and results of the cost benefit analysis are documented in Table 4.

The assumed capital cost for shunt compensation is $40/kVAr and for converters $150/kVA. Cells in Table 4 follow the convention of Microsoft Excel: orange background represents input data, orange text on white background represents linked cells, and black text on gray background are the outputs.

Table 4 Example cost-benefit analysis

UPFC Case code 02	HPFC Case code 25	
94.5	10	Converter ratings [MVA]
0	83.7	Reactive compensation ratings [MVAr]
~14.2	~4.8	Initial Investment [$M]
150	200	Delta Power [MW]
3.76	3.76	Losses [%]
20	20	Valuation of losses [$/MWh]
40	40	Capacity Factor [%]
10	10	Delta Energy Value [$/MWh]
10	10	Hurdle rate [%/year compounded monthly]
17.4	**39.2**	10 year Net Present Value (NPV) [$M]
41	**9**	Payback Period [months]
22.7	**708.1**	10 year Return On Investment (ROI) [%]
2.05	**21.08**	Annual interest rate yielding the same ROI [%]

SUMMARY

This paper presents an example application engineering study selecting a converter-based FACTS compensator to address a commonly occurring power system problem. Two compensators are considered (a UPFC and an HPFC) and an illustrative sizing exercise is performed assuming the common building block for the converters – the MMC.

The findings are promising for converter-based FACTS controllers. Using MMC technology enables optimizing FACTS compensator topology to suit the needs of the applications using the same building blocks. This allows for deployment of FACTS solutions at a reduced technical risk and makes the selection of FACTS compensator an application engineering choice, not a technology one. Furthermore, using the same building blocks allows for standardization of equipment specifications, allowing market participation by many vendors and promising to make converter-based FACTS compensators more cost effective in the future.

The analysis demonstrates that an HPFC can achieve the same system operating point as the real-world UPFC at a significantly lower cost. The calculated payback period in the considered case is 9 months for an HPFC versus 41 for a UPFC. This illustrates the power of customization for a specific application scenario using the common technology platform.

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APPENDIX A

Electrical parameters for the circuit of Figure 2 are as follows.

Value	Parameter
50	fs [Hz]
314.1593	ws [rad/s]
0.423125	Rs [ohm]
3.601522	Xs [ohm]
0.011464	Ls [H]
55.94234	Xm [ohm]
0.17807	Lm [H]
4.975026	XL [ohm]
0.015836	LL [H]
2.5159	Rr [ohm]
15.89332	Xr [ohm]
0.05059	Lr [H]
1.0382	|Us| [pu]
18.6	angle(Us) [deg]
0.9586	|Ur| [pu]
0.0	angle(Ur) [deg]

The system power flows of before and after compensation with the UPFC are tabulated below.

	Before Compensation		After Compensation	
Apparent Power	Re(__) [MW]	Im(__) [MVAr]	Re(__) [MW]	Im(__) [MVAr]
S0	-733.0	-161.3	-881.6	-111.5
S1	-701.8	-154.4	-903.4	-107.1
S2	701.8	154.4	900.0	200.0
S3	700.6	128.5	899.8	158.4
S4	731.7	134.2	878.0	162.3