Current Compensators for Unbalanced Electric Distribution Systems

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***Abstract* — Inherent current imbalances are often present in electric distribution systems due to the increase of single-phase generation in the form of renewables and the existence of single-phase loads. The continued expansion of non-linear load usage is also increasing the levels of harmonics through the power transformers servicing these distribution systems. The issues that arise from these operating conditions are widely known and standard solutions used by utilities are as well. However, they are often bulky and do not provide a level of control or versatility appropriate for these challenges. This paper gives an overview of many of the problems that are faced on distribution systems and how an active shunt compensator may be used to mitigate or eliminate them.**

Keywords— grid-connected converter, power electronics, unbalance compensation, shunt compensator

I. Introduction

Distribution systems normally operate under certain amount of unbalanced loading, especially for residential systems, due to single-phase loads. The issue is exacerbated by single-phase generation in the form of rooftop solar which has seen significant increase in certain areas. Though large-scale three-phase solar generation remains by and large the majority of solar generation this does not eliminate the unbalanced nature of the loading. The issues associated with the negative- and zero-sequence current resulting from unbalanced loads are well documented [1-6]. For example: overheating of a generator, improper sizing of neutral conductors, MMF ripples inside the generator due to negative-sequence MMFs and overheating of the holding tank for ungrounded wye-connected transformers. Efficiency of the total system is also adversely affected [7, 8].

One of the most prominent issues is the voltage profile along the feeder. Utilities use load rebalancing, load-tap changers, and reactive FACTS devices to meet voltage standards. At the three-phase feeder level, there is extensive research into techniques that can be used to optimize tap scheduling and the allocation of load among the available feeders, many of which are summarized in [9]. These algorithms are used to optimize a set of variables, not just load distribution, and many do not consider the effects of load imbalance which can greatly affect the analysis [10]. They also rely heavily on the prediction of the loading curve. This can be difficult when trying to design for new load centers, especially in rural areas [11, 12].

FACTS devices are currently used to augment the existing transmission systems; however, the use of power-electronics-based FACTS at the distribution level is still in its infancy. In this paper, the application of a shunt "unbalanced current static compensator" (UCSC) will be evaluated with respect to (1) the issues mentioned above, (2) a modernizing grid with increasing distributed generation, and (3) an expanding interest in a microgrid-based distribution system.

The remainder of this paper is organized as follows: the main and secondary applications of a shunt compensator are presented in sections II and III, respectively. Simulation results and main implementation challenges for the proposed compensator are given in sections IV and V. Last thoughts are given in section VI.

II. Primary Applications of a Shunt Compensator

Reliability of service is a crucial criterion because customers expect consistent and limitless power availability. This requires a certain amount of margin between the nominal load and maximum feeder ratings at any given time to allow for contingencies. Unbalanced load currents add another level of complexity to the problem because any optimization effort needs to consider each phase of the feeder separately to achieve the true system-level optimal.

An UCSC installed near a distribution substation is shown in Fig. 1. In this configuration on a traditional feeder, a shunt compensator can balance the currents seen by the substation, bring unity power factor (leveraging existing shunt capacitor banks), potentially dampen power oscillations during transient events, and compensate for harmonic currents that are produced by non-linear loads [13, 14].

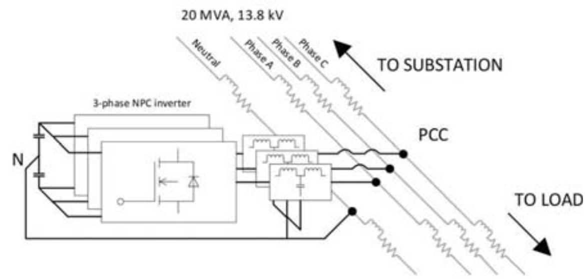

Figure 1. Connection of the UCSC to a three-phase feeder

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A. Current Balancing

When each phase of the feeder is carrying different and varying currents the UCSC can draw additional current from the less loaded phases and circulate that current onto phases that are more heavily loaded. This forces the current seen upstream to the average of the three phases, helping to eliminate any upstream fundamental frequency neutral current. This improves the efficiency of electric machines connected to the grid, can improve the efficiency of the system, and can improve the voltage balance at the point of common coupling by balancing the voltage drop across the upstream impedance [4].

Around 7.7% of billable energy was lost in transmission and distribution systems in the United States in 2016 [15]. Using the average retail price that implies approximately $31.5 billion dollars in lost revenue. Taking a transmission line with equal line resistance and an average current unbalance term, γ, the three-phase currents can be defined as:

$$I_{abc,rms} = \begin{bmatrix} I_{avg}(1+\gamma) \\ I_{avg}(1-\gamma) \\ I_{avg} \end{bmatrix} \quad , \quad 0 \le \gamma \le 1 \tag{1}$$

where I_{avg} is the average RMS current of the phases. The proportional energy loss in the transmission line can be expressed as:

$$E_{3\phi} \propto I_{avg}^2(2\gamma^2+3) \tag{2}$$

In Fig. 2 the lost revenue due to transmission losses is plotted against varying γ for the cases in which transmission line losses amount to 1%, 2%, and 3% of the total billable energy. For the sake of argument, transmission lines were assumed to be operating at a γ of 0.25 for the 7.7% losses quoted above.

These calculations are simple averages that do not reflect the varying nature of loading or $/MWh for the electric power grid, but they do reflect the potential savings for utilities that experience unbalanced loading conditions.

B. Power Factor Regulation

Regulating the power factor to unity helps to improve the total system efficiency by reducing losses accrued in the upstream transmission lines through reactive current reduction. When used in conjunction with relatively cheap and well-known switched shunt capacitor banks the rating of the UCSC can be significantly reduced. While the shunt capacitor banks compensate for most of the reactive power they can only be switched in units of around 50 kVAR per phase [16]. The UCSC can provide nearly infinite steps of reactive power within a smaller range. This

- maintains unity power factor at all operating points,
- reduces potentially the number of operations for the switched capacitor bank and thus, reduces the number transient events from the changing taps in a capacitor bank, and
- can decrease any variations in the voltage profile of the feeder.

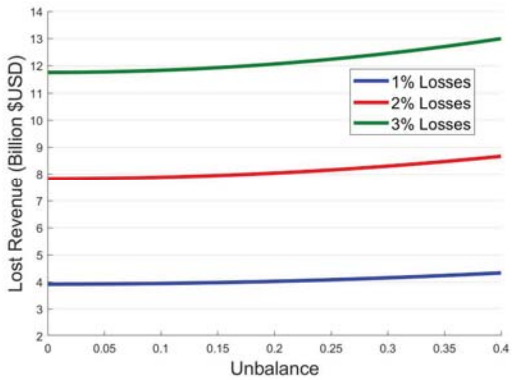

Figure 2. Lost revenue due to unbalances

This operation could be extended to a fault ride-through type operation where the UCSC remains active and provides VAR support for the grid [17].

C. Harmonic Compensation

The UCSC can eliminate the voltage distortion that would otherwise propagate back into the transmission system and other feeders by compensating for harmonic currents. Harmonic voltages can overheat shunt capacitors (decreasing their lifetime), cause increased distortion in other grid-connected converters that are not equipped with harmonic voltage compensation [18], and could excite grid resonant frequencies [16]. Harmonics currents can also over-heat power transformers, creating hot-spots and deteriorating the insulation which reduces the lifetime of the transformer [19].

III. SECONDARY APPLICATIONS OF A SHUNT COMPENSATOR

In addition to the direct benefits discussed above, there are several secondary benefits as listed below:

A. Complements Load Redistribution Practices

By extending the operating range of the upstream equipment, the conditions for load reconfiguration algorithms are laxed and thus provides more flexibility in the solution. This can help to reduce the number of reconfigurations. Currently, utilities manage current imbalances by first attempting to predict the growth of new loads and selectively add new single-phase loads, and secondly, mitigate any imbalances that occur later by moving single-phase loads to other phases as needed. This type of solution decreases the imbalance of the system but does not provide a fine-tuning of the resulting currents, because it does not account for the intermittency of the loads. The presence of the UCSC can extend the amount of time between load reconfigurations. The UCSC also maintains low neutral current at the substation for any intermittent loads. In addition, there may be instances in which there is a fault on one of the loads and a downstream fuse may open. This could cause a significant change in the loading of any phase resulting in an imbalance for which the utility cannot anticipate.

B. *Inter-feeder Current Sharing*

Multiple UCSCs installed at a bus that services several feeders can share a dc-link, providing current redistribution between adjacent substation transformers as in Fig. 3. In this scenario, the total power available to a feeder is no longer limited absolutely by the rating of the transformer servicing it, but by the combined rating of its UCSC and transformer. Or, to approach the problem from a more practical direction, the stress across a transformer can be reduced from near-peak conditions to help prolong its lifetime [20].

If there is a three-phase fault on Feeder #2 and a large current begins to flow through T2, instead of the UCSC on Feeder #2 deactivating, the linked UCSCs can help to distribute some of the current stress of T2 to T1.

C. *Microgrid Augmentation*

In the context of feeders used as microgrids, the UCSC helps to decouple the effects of loads in any one microgrid on the system during grid-connected mode, and in islanded mode the UCSC can operate as a significant STATCOM resource that can help with voltage regulation and sub-synchronous resonances [21]. The compensation capability of the UCSC needs not be limited to the currents directly upstream from the point of installation. Tertiary level controllers for the microgrid can dictate the current references for the UCSC to achieve the goals at other nodes of interest.

D. *Compact Installations*

HV SiC devices enable direct connection to the medium voltages of distribution feeders with significantly less complexity. This eliminates the need for low-frequency transformers and the increased achievable switching frequencies allow for a large reduction in passive components in the power-stage of the device. This enhances the modularity of the UCSC and lends itself to the possibility of incrementally adding UCSC resources to new and existing installations as dictated by load growth or changing optimization criterion for the distribution system.

Component volume reduction and elimination of the low-frequency transformer is important for the cost of the converter, but also for the cost of installation. In [16] the cost of new substation installations in 2008 were as low as \$36/kW or as high as \$110/kW, so being able to eliminate the need for new installations or to be able to pole-mount a FACTS device could remove much of these secondary costs.

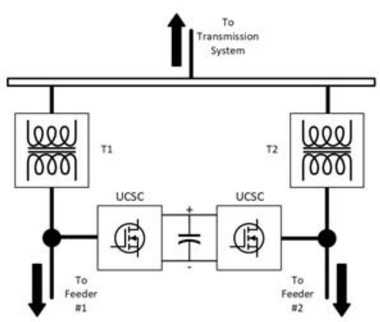

Figure 3. DC-link sharing between UCSC on adjacent feeders

E. *Energy Storage and Delivery*

Though conceived as an energy circulating device, if the UCSC was connected to energy storage or generation it can, with minor changes to its control criterion, supply energy to the load in addition to its other objectives. In the case of energy storage, the UCSC can be used as a peak-shaving device for high-load conditions by storing energy during times of lower cost. And in the presence of renewables like solar and wind this can be used to control the intermittency of loads seen upstream from the point of installation [22].

IV. UCSC Simulation Results

The abilities of the UCSC to balance currents and compensate for power factor are demonstrated Fig. 4 using the control strategy presented in [23] with the UCSC connected directly to a 13.8 kV feeder just downstream from a substation. At t = 0.05 s the UCSC starts to compensate for the reactive component of the load and the current magnitudes reduce accordingly. The power factor is improved from 0.88 lagging to 1.0. At t = 0.15 s current balancing operation begins and the currents of each phase are all brought to the same magnitude. The Unbalance Factor is reduced from 23.5% to 0.15%, and defined by:

$$\mathrm{UBF} = \frac{|negative\ sequence|}{|postive\ sequence|} x100\% \tag{3}$$

Though the merits of the shunt compensator for a traditional feeder are firmly established, their place in a microgrid-based distribution system with significant generation and bi-directional power flows is not as obvious. One can consider a large solar plant installed at the end of the feeder in Fig. 1. At times there may be enough generation on the feeder itself that power flow reverses in one, two, or three phases. The UCSC can still balance the current seen by the substation up to the point and past where the averaged three-phase power flow has reversed. Figure 4 shows the UCSC operating while connected to an unbalanced load while three-phase generation at the end of the feeder increases starting at t = 0.25 s, eventually reversing real power flow in one phase.

The UCSC acting as an active filter for harmonics is shown in Fig. 5, Fig. 6, and Fig. 7 using the control strategy proposed in [24]. The UCSC in Fig. 5 activates at t = 0.03 s

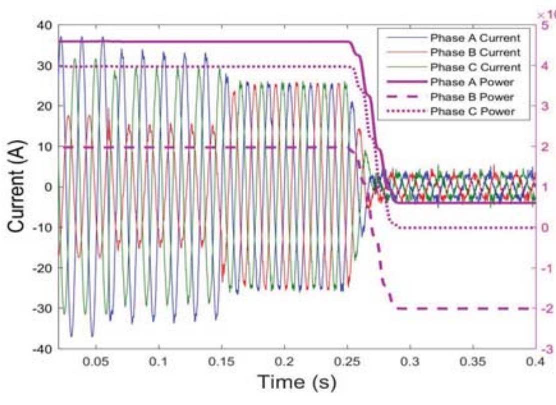

Figure 4. Substation currents and real power demand during UCSC and solar farm operation

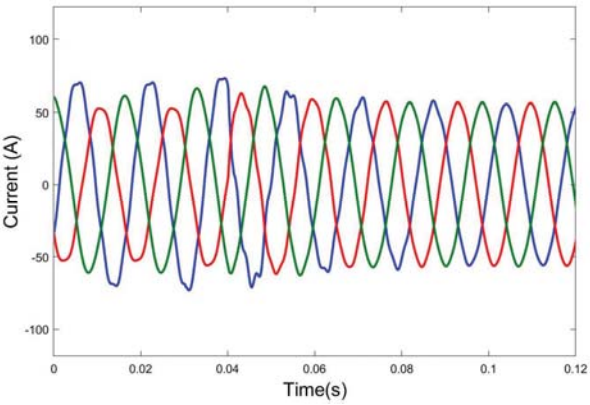

Figure 5. Substation currents before and after harmonic compensation

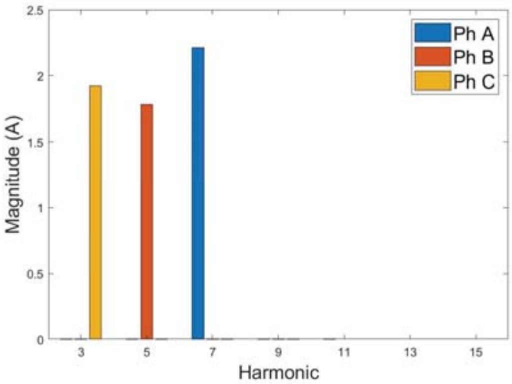

Figure 6. Substation harmonics before compensation

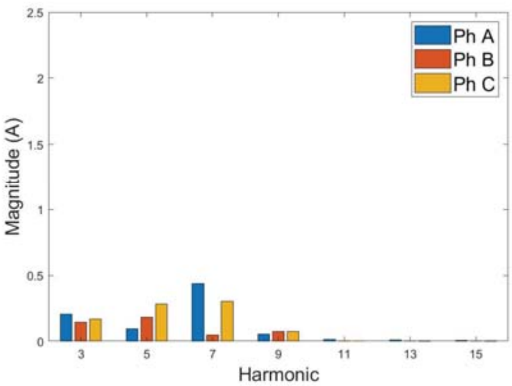

Figure 7. Substation harmonics after compensation

and begins compensation at t = 0.04 s. Figure 6 shows the harmonic content of each substation phase current before compensation begins. The substation harmonics after imbalance and harmonic compensation begins is illustrated in Fig. 7. The 7th harmonic was reduced from 2.2 A to 0.4 A in Phase A. The 5th harmonic was reduced from 1.8 A to 0.2 A in Phase B. And the 3rd harmonic was reduced from 1.9 A to 0.2 A in Phase C. The ability of an active filter to eliminate harmonics is a function of the switching frequency, sampling frequency, and computational power [25, 26].

V. UCSC Technical Challenges

Aside from the issues that any power-electronic-based solution faces (e.g., stability, THD, efficiency), any power electronic solution for the grid faces the same issues of any piece of passive utility equipment: (1) grid transients and (2) internal faults due to these transients. Semiconductor devices do not have the same overvoltage and overcurrent capabilities of traditional utility equipment. Thus, the protection of power electronic based equipment is a prominent research topic. Fortunately, as a supplementary and shunt-connected device, the UCSC avoids many issues that would be faced by equipment like a solid-state substation [27] such as providing fault current in the event of a grid fault and accompanying voltage-sag since the UCSC can quickly deactivate or compensate and wait for the grid to recover.

A. *Over-Voltage Events*

Significant voltage swells can occur on the grid and these types of events can destroy power electronics if the voltage across any of the semiconductor devices rises above their breakdown limit. A worst-case scenario is lightning striking the distribution line near the UCSC. Reference [27] evaluates protections against the lightning strikes. These can include MOVs, solid-state circuit breakers, fault-current limiters, and ac crowbars. Reference [28] evaluates the selected grounding method of a grid-connected converter and its filter components for protection of the converter against lightning strikes using the IEEE 60060 1.2/50μs impulse voltage to approximate the lightning strike on the feeder. With these various solutions there are tradeoffs between cost, voltage surge levels, current surge levels, and any effect the solution may have on the grid.

B. *Internal Faults*

There are more points of failure due to the complexity and component count of these converters. An important area of research is in improving reliability and providing the ability to ride-through the fault of semiconductor devices or capacitors in the converter. Reference [29] outlines the use of redundant switching cells in modular multilevel converters (MMC) to improve reliability in the event of a device failing open or short. Reference [30] evaluates the ability of the flying capacitor converter (FCC, FCMLC) and presents solutions for continued operating after switch faults. "Hot-swapping" of submodule units in multilevel converters like in [31] paired with redundant switches or switch over-ratings can also enable smaller or eliminate down-time for power electronic equipment.

Another point of failure in most converters is the capacitor. Electrolytic capacitors can be a major limiting factor when it comes to the lifetime of the converter. Reference [32] addresses the reliability of capacitor banks based on electrolytic and film type capacitors. Film capacitors generally have greater reliability than electrolytic capacitors, but a lower energy density leading to an inherent tradeoff between cost, size, and reliability. However, the higher switching frequencies enabled by SiC devices can shrink the capacitance required in some converters, which can make this trade-off optimization effort easier.

Though SiC is an enabling technology for direct MV connection, it brings new cabinet- and PCB-level design challenges. Powering gate drive circuitry at 10-30 kV bias with dv/dt of 100 kV/μs requires careful design of power supplies [33, 34]. Self-powered gate driving architectures may also be a suitable solution [35]. The selection of isolation materials is also important [36]. Reference [31] uses a solid polyurethane dielectric for a reduction in direct clearance between components, and thus converter volume, and as mechanical support for each submodule in the MMC.

C. Converter Start-Up

In general, power converters require a start-up procedure and additional equipment to avoid high in-rush currents leading to power device failures. This actuality, like in grid transient protection schemes, requires some trade-offs between complexity, cost, and volume in the solution. As suggested in [37] a pre-charge resistance can be used to charge the capacitors in the converter safely, by limiting the in-rush current when the breaker is closed. This requires the use of an additional medium-voltage switch across this resistance to short it out during normal converter operation, which all together is relatively cheap, but can take up a lot of volume. The other common method is the use of an auxiliary power supply that charges the capacitors using energy from the grid in a controlled manor [38]. This can be implemented with semiconductor devices with potentially less volume than the shunt resistor method, though it is more complex and expensive. In both scenarios there is the potential for a mismatch in the capacitor voltages. Balancing resistors and PWM techniques can be used to eliminate this mismatch during the start-up transient and steady-state operation as suggested in [39].

VI. Conclusions

The use of an Unbalanced Current Static Compensator as a shunt compensator was evaluated for its use in electric distribution systems. The UCSC's primary functions as current balancing and power-factor correcting device were shown in simulations of a 13.8 kV feeder. The UCSC was able to achieve negligible neutral current and unity power factor for each phase. In addition, simulations of the UCSC acting as an active filter for harmonic currents were also included. The amplitudes of the 3^{rd}, 5^{th}, and 7^{th} harmonics were reduced by around 80%. Potential secondary functionality of the UCSC and their benefits to the distribution system and the utility were discussed.

Current challenges associated with the implementation of grid-connected power electronics and more specifically multi-level converter structures based on SiC were presented along with solutions that have been proposed to solve these problems. This shows that the underlying technologies required to make a medium-voltage active compensator plausible exist. Though further research into reliability, cabinet-level design and proof-of-concept testing at medium-voltages approaching the 15 kV-class distribution voltages like in [40] are needed to increase confidence in the viability of FACTS implemented at the distribution system level.

Acknowledgments

The authors are grateful for initial financial support from the NSF I/UCRC Grid-Connected Advanced Power Electronic Systems (GRAPES) under grant IIP-1439700. The authors are also grateful for the financial support through a tailored collaboration project between EPRI, Southern Company and Arkansas Electric Cooperative Corp.

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