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Highly Compact Transformerless Universal Power-Flow and Quality Control Circuit

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***Abstract*—This paper presents a novel, highly compact direct-injection modular universal power flow and quality control topology exclusively using lower power components. In addition to conventional high-voltage applications, it is particularly attractive for the distribution grid down to low voltage as it can exploit the latest developments in low-voltage high-current semiconductors. The distribution grid is under immense pressure due to rapid growth of high-power loads and sources, such as vehicle chargers and photovoltaic installations, which can locally overload lines and generate both over- and under-voltage conditions in the same grid section so that conventional voltage adjustment through transformer tap changers fails. In contrast to conventional universal power flow and/or quality controllers (UPFC, UPQC) or soft-open point (SOP) circuits, the concept both eliminates any injection transformer, which is large, costly, and limited in dynamics and the need to convert the full grid power. The presented direct-injection circuit exploits the recent developments in high-current low-voltage transistors. The centre piece is a low-voltage module connected in series with each phase, which is floating with the grid voltage so that it only needs to deal with a small voltage difference between its outputs and can maintain that condition also under fault currents of several kiloampères. Due to the low-impedance of the distribution grid, only a few volts are sufficient to control several hundred ampères in active and reactive current in a loop. In contrast to commercially available transformer-injection-based SOP solutions with often considerable additional loss, the injection modules have almost negligible additional impedance (< 4 mΩ).**

***Keywords*—Mesh current control, power flow control, power quality, distribution grid, unified power flow controller (UPFC), unified power quality conditioner (UPQC), soft open point (SOP), direct-injection universal power and quality controller (DI-UPF/QC).**

I. Introduction

As a previously mostly mechanical and simple electromagnetic system with a well-defined mostly unidirectional power flow from the higher-voltage generation and transmission to lower-voltage distribution and consumption, our electrical energy grid is undergoing an immense transformation. In addition to the formerly clear power-flow conditions, conventional tolerant and inert loads (grid-connected motors and pumps, light, heating, etc.) as well as energy sources (large generators) are increasingly replaced by rapidly-responding feed-back-controlled electronics [1, 2]. This transformation also needs the grid to respond to the changes with appropriate elements. In the high-voltage grid, electronification for higher controllability and increased capacity has been initiated as such a response already decades ago and even standardised and codified in the flexible ac transmission system (FACTS) catalogue [3-9].

The distribution system, however, is still widely uncontrolled and in many places also just marginally monitored compared to the high-voltage grid. Sometimes more than even the medium-voltage grid, the low-voltage grid is under particular pressure. Rapidly increasing distributed photovoltaic generation with growing power levels even in residential set-ups introduce generation into the distribution grid, which can bypass the monitoring of utility companies, have rapid control response, and typically cannot contribute to the short-circuit capacitance, while also (electronic) loads increase in power, with more and more powerful public and personal vehicle chargers or the increasing electrification of heating systems with heat pumps [10-15].

The widely uncontrolled installation and operation of such systems can lead to undesired power flows that locally overload lines, e.g., when one or several powerful photovoltaic installations feed vehicle chargers in the vicinity, bypassing any substation and monitoring. In addition to local overload and congestion, unintended power flows can concurrently cause over- and under-voltage conditions in the same grid segment. Such voltage violation can be strong enough to locally leave the typical ±5% or even ±10% bands [16]. With both conditions in the same branch and even at the same time, transformers with tap changers or electronic equivalents are no solution [16, 17]. Increasingly meshing the low-voltage grid and installing switches that are normally open (normally open points) can improve the situation to some degree, but still require notably more information about the present flows than are available at the moment and the resulting flow is still passive [18-20]. Furthermore, such relatively static and binary connections can export the problem to the next grid level, unnecessarily increasing loss.

In high-voltage grids, universal power flow controllers (UPFCs) are a well-established part of FACTS and allow, in addition to power quality improvement, also the accurate control of power flows in rings [6, 21]. Soft-open points (SOPs), either implemented as ac-to-dc-back-to-ac converter for the full power flowing along the line or UPFC, are intensively studied and tested to solve the issue [22-24]. Furthermore, these circuits may serve for mitigating power quality problems under the label unified power quality conditioner (UPQC) [25, 26].

If UPFC, UPQC, and soft open point circuits do not convert the entire power, i.e., full grid voltage and entire current, from ac to dc and back to ac to more or less re-establish the grid on the other side, they traditionally consists of a common dc link, a shunt voltage source converter, and a series voltage-source converter, coupling to the transmission line through transformers on both sides [27]. The converters can, use any known converter technology, such as simple two-level or neutral-point-clamped inverters for lower voltages or modular multilevel converters for higher voltages [28-33]. However, the bulky series-injection transformer is an essential element of most known solutions and often dominates the electronics with respect to size. The series-injection transformer needs sufficient thermal and magnetic rating for the full line current and additional losses, which leads to large installations. Furthermore, these transformers have very limited dynamical response so that the compensation of higher-

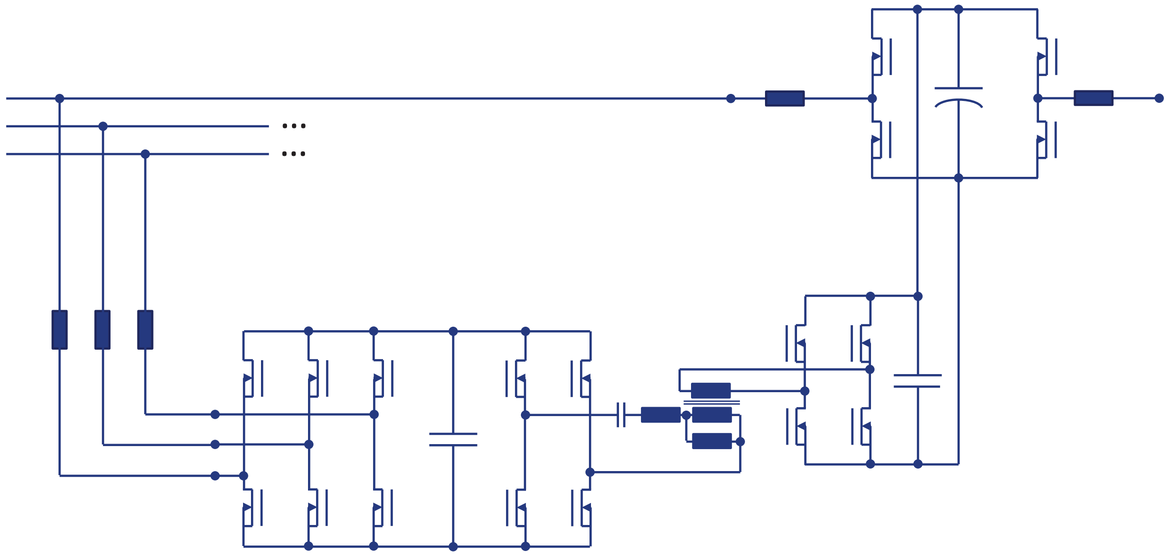

Fig. 1. Circuit configuration of the transformerless direct-injection UPFF/QC, e.g., for soft open points.

order harmonics is lossy or impossible [34, 35]. Due to these massive disadvantages, recent research aims at eliminating transformers [36-41]. However, the suggested solutions then typically need to deal with the full line voltages and currents.

This paper proposes a novel circuit for UPFCs, UPQCs, and soft open points. The circuit principle allows active/reactive power compensation, harmonics reduction, voltage vector adjustments, and active as well as reactive power flow amplitude/direction control. It is applicable to both high-voltage and low-voltage applications. The use of latest high-current low-voltage semiconductors is particularly attractive for meshed low-voltage grids, where it can control the flow at nodes or in loops. The proposed topology does not use any grid-connected low-frequency transformers, neither in the shunt part nor in the series injection. Due to the omission of any grid-frequency transformers, the circuit can achieve unparalleled power density and response dynamics.

II. Circuit Topology and Principle of Operation

The system configuration is shown in Fig. 1. It uses a full-grid-voltage but low-current shunt grid front end feeding a shared dc link from which three bidirectional dc/dc converters, one per phase, acting as power supplies for the core element of the circuit, specifically three floating high-current low-voltage series modules. The series modules can inject a vectorial voltage into the line voltage to adjust the phase voltages or control the current flowing across that point.

The design leverages on our previous work on modular floating, high-voltage low-current, and low-voltage high-current circuits [42-49]. The proposed concept uses a grid-voltage low-current supply and low-voltage high-current modules floating with the line potential. The reduction of the problem to these two voltage–current ranges exploits the development of power semiconductors of recent years driven by consumer electronics, appliances, and the automotive industry to achieve enormous power density and dynamics [50, 51].

The circuit design further combines several concepts to avoid both shortcomings of the prior art, specifically (1) bulky low-frequency transformers and (2) electronic components that need to have both high current and high voltage ratings at the same time. Due to the relatively low impedance of the grid, already a rather small voltage difference in a loop can already drive rather large currents and powers with a series injection. For low-voltage distribution grids, sufficient driving voltages can be as low as 5–10 V [13, 37, 52]. Furthermore, the voltage is nowhere allowed to leave a ±10% window anyways, limiting the necessary amplitude even under severest conditions.

Still, the entire grid current has to be lifted or reduced by the injected voltage. These currents can reach hundreds of amperes under normal conditions and kiloampères during faults for the example of a low-voltage grid. The fault currents are typically primarily limited by the short-circuit impedance of the feeding transformer, potentially reduced further by line impedances. Without any ground connection, the floating modules only need to generate and control the small voltage difference and the current (Fig. 1). The power actively injected or extracted, on the other hand, is low to moderate for power-flow control, while power-factor correction and harmonics compensation do practically not involve any active power beyond compensating losses and are compensated by either the module or the shared dc link. Thus, the power of the supply and shunt circuit will need to connect to the grid voltage like any simple conventional power supply, but the current is low to moderate.

As outlined above, the circuit contains two parts, specifically an isolated power supply with parallel grid interface and a floating series injection module. For four-quadrant operation and control power flow from a higher-voltage to a lower-voltage feeder, a bidirectional power supply is required. We suggest a shared active front end (AFE) and a shared dc link in combination with one bidirectional resonant dc/dc converter per module for isolation and to reduce the voltage of the shared dc link to the module supply voltage level. The AFE can serve as a highly dynamic shunt converter following known concepts [53]. Moreover, it absorbs or supplies active and reactive power to the dc link of the floating module. The shared dc link behind the AFE allows different asymmetric load conditions on the AFE and the module side while power can be exchanged between the phases.

The isolated dc/dc converters do not need tight voltage control so that LLCs can transfer the voltage of the shared dc link

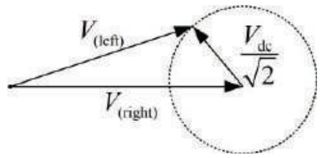

Fig. 2 Phasor diagram of two grids and the floating module.

with a fixed voltage ratio from the grid-level higher voltage to the module-level lower voltage. The isolation allows each module to float with its corresponding line potential. Although practically any isolating bidirectional dc/dc topology suffices, an LLC provides high efficiency in resonance, low electromagnetic interference, and a relatively constant voltage ratio also under open-loop operation [54-56].

As the centre piece, one floating module supplied through a dedicated dc/dc converter is in series with each grid phase. Each module contains a dc capacitance, a transistor H bridge, and at least one grid inductor. As the floating modules follow the electrical potential of their dedicated phase and do not have any electrical connection to ground or the other phases, the local voltages are small, e.g., below 48 V for low-voltage grids. In the case of low-voltage grids, the modules accordingly are exclusively low-voltage units and can use low-voltage capacitors and transistors. Driven by automotive and consumer electronics, latest field-effect transistors (FET) offer exceptional high-current capabilities below 100 V [50, 51, 57]. For the medium-voltage distribution grid, the necessary module voltages fall well within the semiconductor ranges for electric vehicle drive trains and industrial drives. Each floating module can inject a series voltage into the corresponding phase, notwithstanding the notably higher voltage to ground.

The floating design allows the modules to control large power flows with only a fraction of that power, injecting or extracting only the necessary difference voltage and associated power. Furthermore, the direct electronic interface without any transformer enables current and/or voltage control with a wide bandwidth into the kilohertz range. Overall, the modules handle the full grid current but with only a fraction of the grid voltage, which is sufficient to control the power flow, shift the phase, or inject/absorb harmonics. The dc/dc converters are already exposed to less power and only need to provide the power injected into the grid (from pushing current from a lower-voltage to a higher-voltage feeder) and losses (from phase-shifting or harmonics injection) or remove the power extracted from the grid (from slowing down the current flow from a higher-voltage grid segment to a lower-voltage one) with the output side at the module dc voltage, e.g., 48 V here, and the input on the grid level, e.g.., 650 V. The AFE component it not new and can follow known topologies as well as control principles from the prior art. It only converts the net real power left after the shared dc link capacitor and moderate current levels.

III. Operation Range

If different feeders or branches of a grid loop is connected to the two sides of the floating modules, the grid on each side can have different amplitude and phase. According to the phasor diagram in Fig. 2, the floating module can bridge the difference between two grids to stop current flowing or run a very controlled flow between the two grid connections.

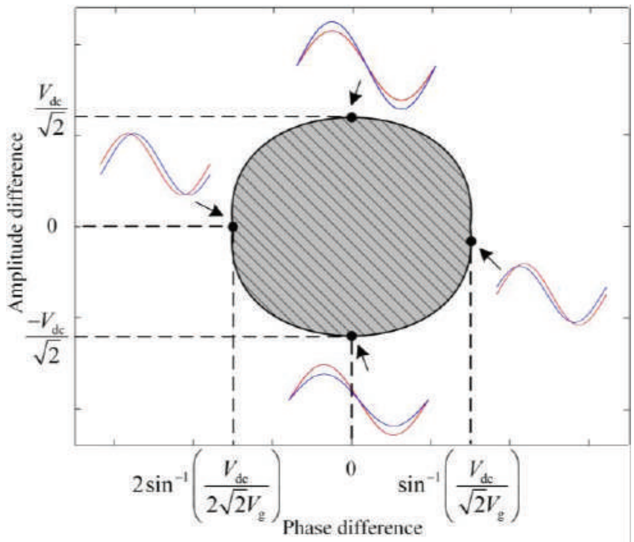

Fig. 3. Coverage of the floating module connecting two grids or feeders without over-modulation. With over-modulation, the voltage reserve can increase by 25% or even 40% in exceptional situations.

For a compensation of the voltage difference, the floating modules at each time instance generate exactly the difference between the two grid voltages. In consequence, no current is flowing. If the floating modules undercompensate the voltage difference (and/or shifts it in phase), a residual current is flowing from the slightly higher voltage side to the lower voltage one. Under voltage control, the resulting current depends on the grid impedances, whereas current control can regulate them directly. Furthermore, the floating modules absorb the power of voltage difference times the currents flowing across them in their low-voltage dc links. This energy is transferred back to the shared high-voltage dc link by the LLCs. By injecting energy from their dc links, the floating modules can even reverse the direction of power flow by figuratively pumping active (and/or reactive) current against the voltage potential through setting a larger (and/or phase-shifted) voltage between both than the nominal voltage difference between left and right side.

Consequently, the floating modules' dc-link voltage constrains how large the amplitude and phase difference between two grids or grid segments can be so that the system can still bridge the gap in between. Fig. 3 illustrates the operation range. The actual grid voltage V_g is defined as the average of the left and the right grid voltage (i.e., $V_g = ½(V_{(\text{left})} + V_{(\text{right})})$) to avoid defining a nominal side so that the system and the plot are symmetric. With over-modulation, the range can be extended beyond the outer limit [58]. However, over-modulation would necessarily inject harmonics and therefore may rather serve as a fallback option if in exceptional cases larger voltage amplitude and/or phase differences need to be bridged.

For our experimental setup of 230 V nominal effective grid and 48 V floating-module voltage, the specific limits would be 34 V and 8.49° (48 V and 12° with over-modulation), which well exceed the grid voltage tolerance of ±10% per IEC 60038. Fig. 10 illustrates the case of the maximum in-phase voltage difference, where the floating modules operate at the maximum modulation index without over-modulation. The limits are

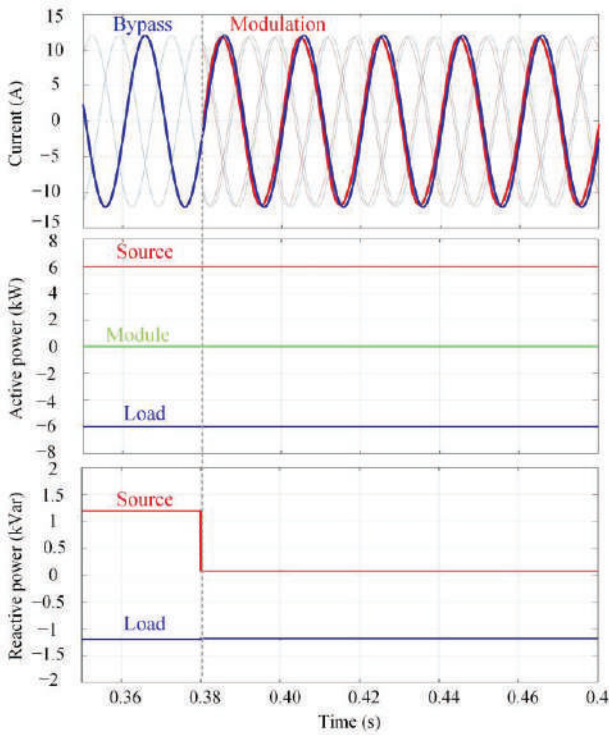

Fig. 4. Current, active power, and reactive power for the RL load case (only active power passing through).

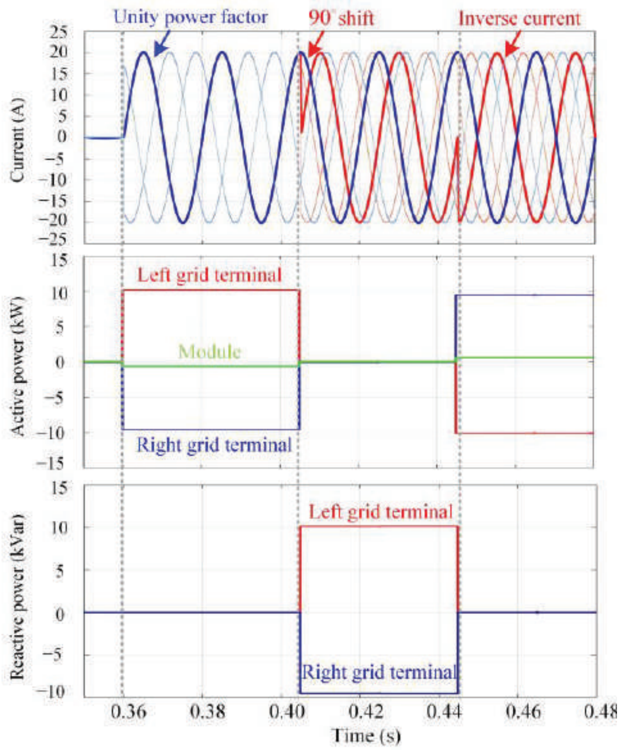

Fig. 5. Current, active power, and reactive power for the two grids case (same phase and different amplitude)

$|V_{(\mathrm{left})}-V_{(\mathrm{right})}| \le V_{\mathrm{dc}}/\sqrt{2}$ ($|V_{(\mathrm{left})}-V_{(\mathrm{right})}| \le V_{\mathrm{dc}}$ with over-modulation). In case of voltage parity, the system can manage a maximum phase difference β according to

$$V_g \cdot \sin\left(\frac{\beta}{2}\right) = \frac{V_{dc}}{2\sqrt{2}}.$$

IV. Simulation and Experimental Results

A. Simulation results

We modelled the circuit and associated control in Matlab/Simulink to analyse the performance. The line rating sets the necessary power-flow reserve. The grid or load and floating-module voltage rating determine the minimum dc-link voltage as derived analytically above. We analyse several situations with mixed active–reactive load (RL) with only active power passing through, mixed active–reactive load with only reactive power passing through, two grid feeders with different amplitude, two feeders with different phases, and mixed active–reactive load with harmonics.

As discussed above, the floating module can compensate all the reactive power for loads within the limits of Eq. (1). In Fig. 4, the controller switches from bypass to active flow control at t = 0.38 s. At that point, the grid and the load voltages get phase-shifted relative to each other. Therefore, the line current shifts left compared to that without modulation (dark lines for the first phase, faint lines for second and third phase). From that time onwards, the floating modules shield off the reactive power from the source grid so that its contribution drops from 1.2 kVar to approximately 0. The reactive power is maintained and delivered by the floating modules, where the dc-link capacitor absorbs the fluctuation before it enters the grid.

From the line end, we can see the reactive components are filtered out. Therefore, a phase difference between the line current in the modulation mode (red line) and its otherwise unchanged current (blue line) occurs. The lighter lines are the other two phases. The electrical system is now corrected to unity power factor, as seen from the source end, and the grid voltage will be perfectly in phase with the line current. The active power remains constant as the control in this mode does not target the active power.

In Fig. 5, the floating modules connect two grids or feeders with different voltage amplitude. Without flow regulation, a large current would rush into the lower-voltage grid segment, risking damage of the distribution cable. Therefore, the power-flow controller suppresses any current flow through generating the series voltage in the beginning. From 0.36 s on, the series modules control the current to 20 A from the higher-voltage to the lower-voltage grid segment with unity power factor. The floating modules consume the excess power. For the subsequent interval, the system shifts the line current by 90°, resulting in a purely reactive power flow.

To demonstrate the fully bidirectional capability, the last interval shifts the current by another 90°, leading to an active power flow from the lower-voltage to the higher-voltage grid segment against the voltage gradient. The necessary power to push the current against the voltage is provided by the dc link.

If grid segments with identical voltage but different phase are connected through the power-flow controller, the bypass mode would likewise lead to unacceptably large currents only limited by the grid impedance. Therefore, the controller regulates the current to zero in the first interval of Fig. 6, generating the necessary voltage difference. The figure further demonstrates bidirectional active and reactive power flow equivalent to the case of grids with different voltage amplitudes.

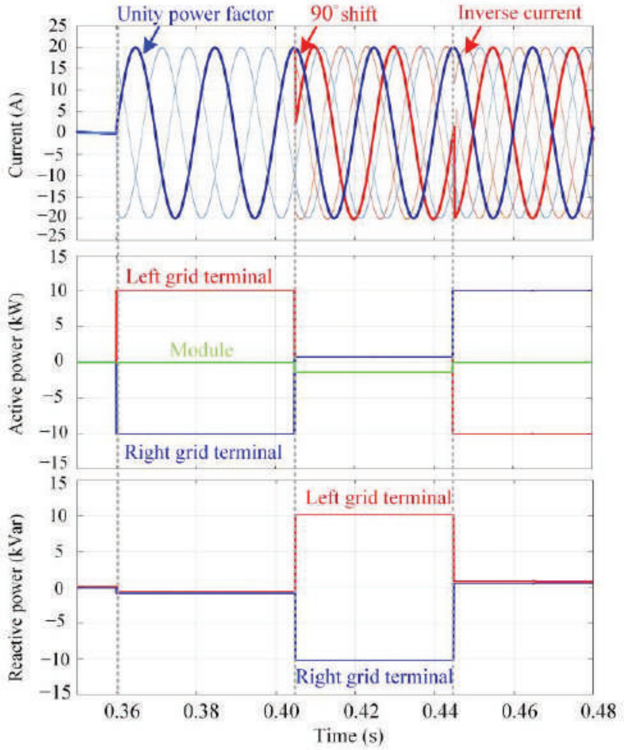

Fig. 6. Current, active power, and reactive power for the two grids case (same amplitude and different phase).

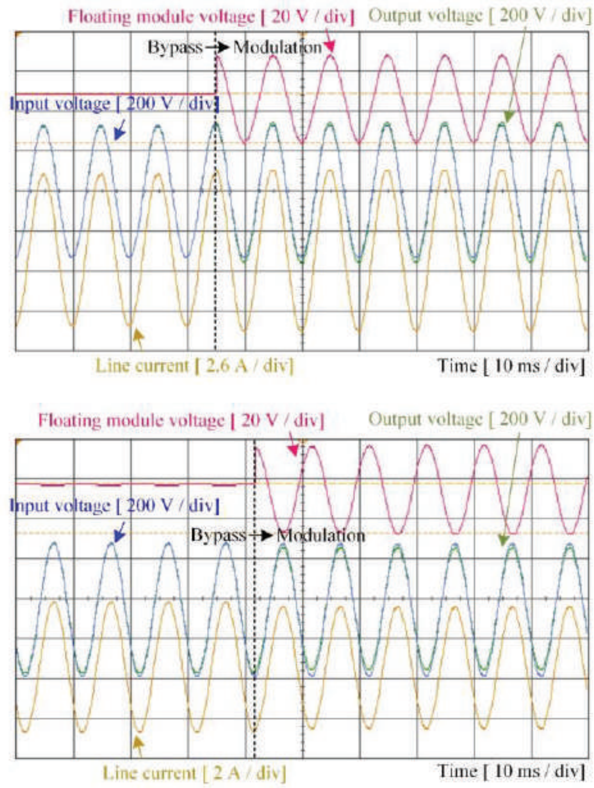

Fig. 7. Measured voltage injection.

B. Experimental results

We implemented an experimental system to further substantiate the simulations. The floating modules implemented low-voltage high-current silicon transistors (Infineon IPT015N10) supplied through LLCs. With a dc link voltage of approximately 48 V, the modules cover the above-derived differences of 34 V and 8.49° (48 V and 12° with over-modulation) between the series-injection terminals. With only 126 mm × 75 mm, the modules can continuously run at least 500 A and more than 2,500 A for a short time in case of a grid fault. A digital signal processor (Texas Instruments TMS320f28379) controlled the setup through standard signal isolators on the modules.

Fig. 7 demonstrates the ability of the floating module to adjust the voltage between its terminals for one feeder and load connected to the other side. Initially, the series-injection module is operated in the bypass state so that the current passes through unchanged. In the top trace, the circuit switches to active voltage control some 30 ms into the recording and increases the voltage, injecting power from the grid through the series modules. In the bottom trace, the modules reduce the voltage. As voltage decrease and current are in opposite direction, the modules effectively extract power, which is fed back to the shared dc link.

V. Conclusion

We presented a fully electronic direct-injection modular power-flow controller that avoids any bulky grid-frequency transformers. Due to the need of only managing a fraction of the grid voltage in the floating modules in combination with recent power semiconductor developments around a kilovolt and below 100 V, the concept is particularly attractive in the distribution grid (e.g., 120 V/240 V/480 V, 230 V/400 V, and 10 kV – 30 kV). In contrast to other fully electronic power-flow topologies, the concept neither needs to convert the entire power flowing through a line not use bulky and problematic transformers. Instead, the floating direct-injection modules only inject or extract a small voltage phasor on top. The topology includes low-voltage high-current modules that float with the phase potential and a full-voltage low-current shunt converter. The floating modules can exploit latest automotive- and consumer-electronics-driven developments of silicon transistors for 48 V units and electric drive trains with high current densities reaching several hundred to thousand amperes. Despite the limited voltage reserve in the floating modules, even 48 V are sufficient to cover voltage differences of ±15% in 230 V grids and ±31% in 110 V grids, while further over-modulation can expand the operating range in case of exceptional events. For medium voltage distribution grids, 1,500 V floating module voltage can, for example cover ±10% in a 10 kV line without and up to ±15%, with over-modulation. The active front-end can operate as a passive power supply or a shunt compensator as long established in the prior art. The compact circuit allows bidirectional active and reactive power-flow control as well as harmonics injection or blocking with only minor adjustment of control methods known from conventional UPFC, UPQC, and soft open point circuits.

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