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Power quality and efficiency functionalities for a three-level Dynamic Voltage Restorer on low voltage grids

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Abstract. Back-to-back PWM inverter based bidirectional dynamic voltage restorers (DVR) may have worse efficiency than mechanical or SCR based solutions, but they are able to provide a continuously variable voltage in series with the grid. As the injected waveform does not need to be sinusoidal, additional features may also be implemented in software. In this paper it is shown that the compensation of voltage harmonics, flicker, and even voltage transients are all possible to some extent. The power required for the series voltage injection does not need to originate from the same phase where it is injected. Drawing power from the less problematic phases can also be used to increase the voltage symmetry on the unregulated side of the device. It is shown in the paper, that at partial load the complete deactivation of one phase in the active rectifier stage can not only help with asymmetry, but can also increase the efficiency of the system. A method is proposed for the seamless transfer in the active rectifier stage from 3-phase to 2-phase operation and back. It is also shown in the paper, that phase deactivation and electronic bypass of the injection transformer is possible in the output stage as well. The three level half bridge circuit configuration enables this without additional components.

Key words. compensation, DVR, flicker, harmonics, seamless transfer, three level, phase deactivation

1. Introduction

The need for autonomous voltage control methods on low voltage grids is increasing among utility companies. The voltage variations on low- and medium voltage grids are often independent from each other. One of the main causes of such problems is the increasing penetration of small scale grid-connected PV generation in rural or residential areas. For keeping the voltage within the limits guaranteed within utility contracts, central solutions like on-load tap changing transformers might not be sufficient. On long branches of low voltage distribution grid, voltage drop might change to voltage increase during hours of local over-generation. The use of bidirectional series, active voltage regulating elements (Fig.1) can be useful with careful placement [1]. Most classical solutions available on the market usually use mechanical contactors or thyristors to switch transformer taps on the series

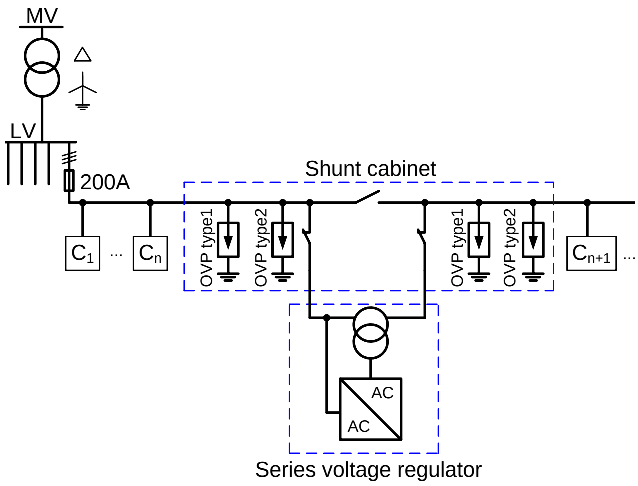

Fig.1. Single line schematic of DVR on low voltage grid. C_n shows the individual customers.

injecting transformers and / or on an autotransformer used to supply the injecting transformers in binary steps [2]. Switch-over between taps may cause transients or flicker. Another problem with such solutions is that the power used to raise voltage in a phase wire is drawn from that same phase wire, exacerbating the problem on part of the line immediately before the series regulating device.

Inverter based Dynamic Voltage Restorers are much more versatile [3] [4] and can be used for other purposes as well. Most applications are limited to large, central medium voltage devices. Experience with medium voltage devices is available in literature [5]. Some systems use battery or ultracapacitor energy storage [6]; these can also supply active power and may not need an active frontend stage. Direct solar feed-in is also possible [7]. Inverter based solutions can have additional features like fault current interruption [8] or harmonic compensation [9].

To solve the problems described above, an inverter based solution has been in development since 2018 in cooperation with E.ON Hungary, BME VET, BME AUT, and PROCON DRIVESYSTEM Ltd (Fig.2).

The topology (Fig.3) consists of two main parts: The input

Fig.2. PROCON “DVR-15” unit for 3x 230 V 200 A grid

stage is a 3-level bidirectional active rectifier stage which regulates the internal DC voltage of the capacitor bank to 650 V. The star point of the AC capacitor bank was connected to the DC midpoint for EMC reasons. The internal DC bus is used to feed another identical power stage which is configured as three independent inverters in single phase 3-level half bridge configuration. These are capable of driving the 230 V low current side of the three 5 kVA 10:1 single phase toroidal transformers. The isolated 23 V winding of each transformer is connected in series with a grid phase, allowing for a continuously variable series voltage injection up to ±23 Vrms at 50 Hz. The unit also contains a thyristor-based overvoltage protection device, which can shunt the transformer secondaries until the bypass relay operates.

After the first prototype has successfully operated in the field for 3 years, the device has been redesigned based on operational experience. Further research has been performed related to additional software functionalities. These include voltage harmonic and flicker cancellation via inverted series voltage injection independently in all phases. The results have been implemented and laboratory tested on working units. The efficiency of the system has also been improved using the bypass capability of the 3-level half bridge topology. Further research was done to

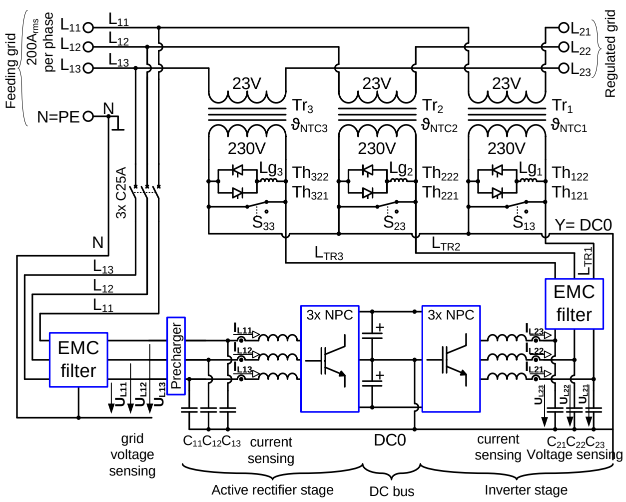

Fig.3. Power circuit of the proposed series voltage regulator

perform seamless transfer from 3-phase to 2-phase operation in the active rectifier stage and reduce switching losses. The 2-phase operation has an additional bonus because the unused phase can be chosen based on phase voltage. Not using the most problematic phase can help in asymmetrical grid voltage scenarios, as the power injected into that phase may originate as 2-phase power drawn from other phases.

2. Control

The block diagram of the control of both stages can be understood based on Fig 4. The active rectifier stage follows the conventional arrangement of midpoint balancing, third harmonic modulation, and vector PI current control scheme with cascade PI voltage control. The votage control is intentionally slow and its feedback is from a 10ms moving average of the internal DC voltage. This allows the 100 Hz fluctuation of the internal DC bus, so the fluctuating DC power demand caused by asymmetrical or single phase injection can be spread across phases by the active rectifier. In case of extreme sudden load changes, this slow control might not be capable of keeping the DC voltage within limits, so a fast control can automatically activate if needed.

A. Voltage Identification

Another important task of the active rectifier control MCU is to determine the required injected voltages. This is done using the sensed AC voltage values. A three phase PLL is responsible for grid synchronization. Discrete Fourier decomposition of the sensed phase voltages is then used to identify cosinusiodal and sinusoidal fundamental and harmonic components of the phase voltages. Filters with 100ms time constant are used for all harmonics. The sinusoidal and cosinusoidal components of the fundamental AC reference voltage vector *Vref* are then subtracted from the fundamental component of the measured voltage. The error is saturated to 23 V rms, and is sent via CAN bus to the microcontroller of the output inverter for series injection.

B. Series Harmonic and Flicker Compensation

The harmonic compensation feature was added the same way as for the fundamental component. Only the identified odd harmonics are transferred to the output inverter, as unsymmetrical waveforms containing even components were found to cause injection core saturation in extreme cases. As the two inverters are synchronized to each other, the identified inverted harmonic waveforms can be injected with minimum phase error, causing this method to be quite effective.

Flicker and transient compensation has been performed by sampling the whole low frequency part of the remaining measured voltage at 1ms sample rate. DC and harmonics are identified and removed from the stream in the active rectifier control software before the anti alias low pass filter stage. This is necessary to avoid asymmetrical periodic waveforms which could increase the probability of injection transformer core saturation. Because the waveform might not be periodic, certain delay and phase error is inevitable due to filtering and sampling. However, at frequencies below 10 Hz this was calculated to be less than 10°, so a significant degree of compensation could be

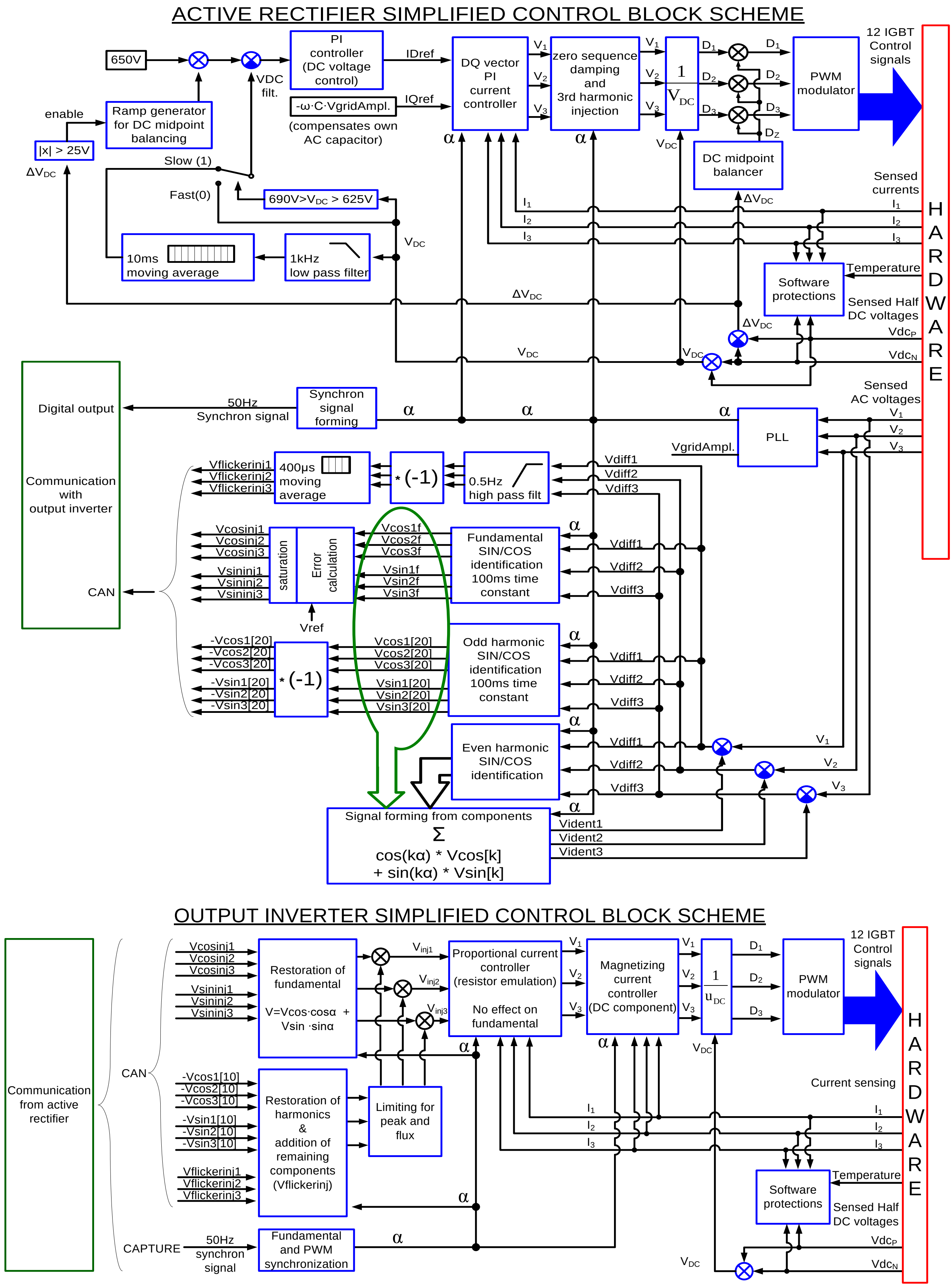

Fig. 4. Simplified control block diagram of the active rectifier and the output inverter stages, the latter drives the injection transformers

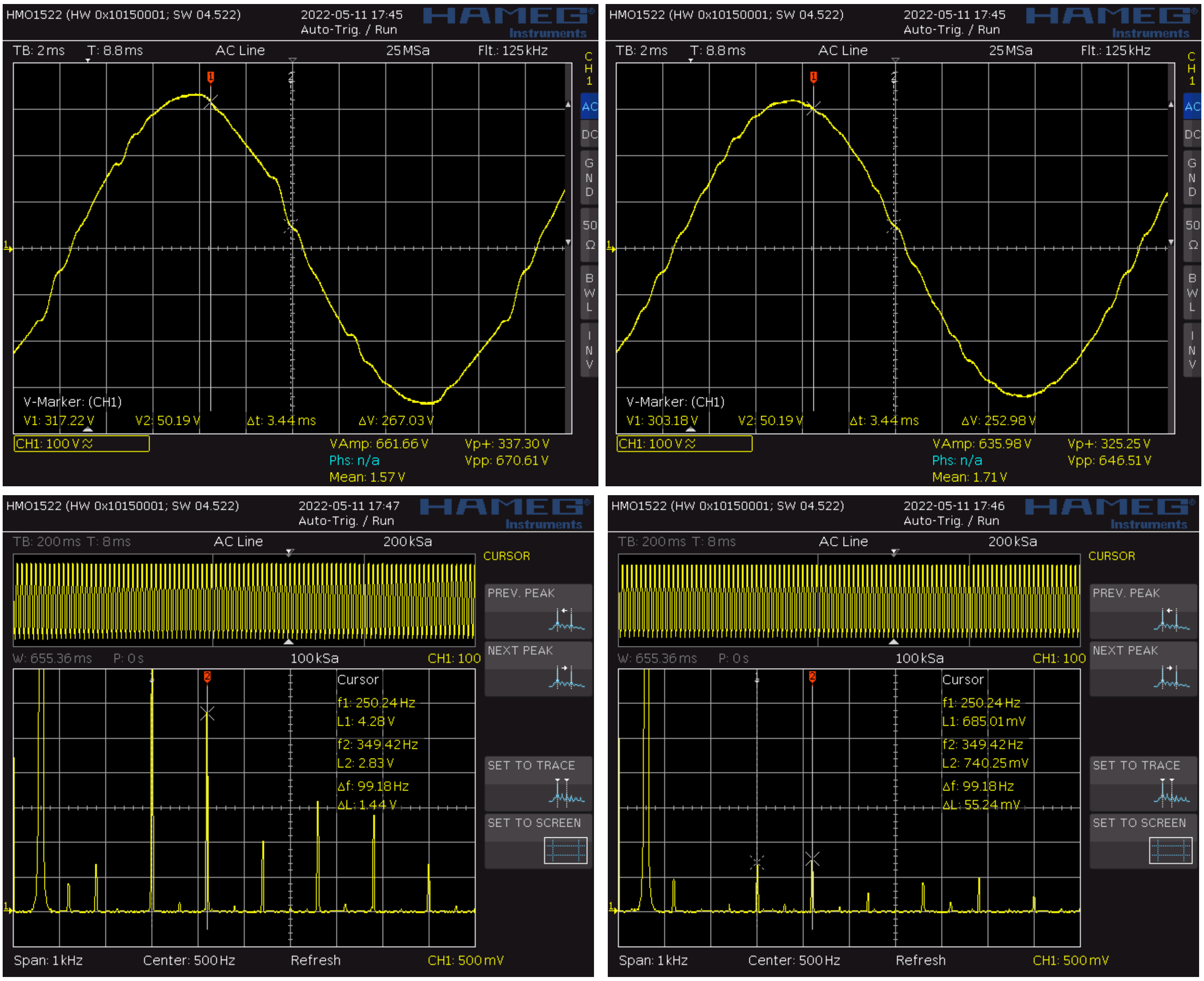

Fig. 5. Series harmonic voltage compensation results. input (left) and output (right). Waveforms are on top, spectra on the bottom figures.

expected. All data (fundamental, odd harmonics up to 19th harmonic, and sampled low frequency part) are sent through a 1Mbit CAN bus to the controller of the output inverter stage every millisecond. The voltage waveforms required for harmonic compensation are then regenerated by the control software of the output inverter from its spectral components, and the sampled low frequency waveforms are added.

Limiting of the peak injected voltage and the peak flux are both necessary. Injected voltage is limited by the available DC voltage, and the peak flux is limited by the saturation of the injection transformer core [10]. The peak voltage and peak flux of the highly complicated injected waveform would be hard to calculate in advance even for harmonic compensation only. With the sampled low frequency part added, this is not feasible. Peak detectors were used instead using very slow (10 second) time constants. Fundamental injection has priority over harmonics and flicker compensation, which can use the remaining available voltage and flux margins.

C. Results with Harmonic and Flicker Compensation

Results with the described harmonic compensation method can be seen in Fig. 5. The uncompensated waveforms were measured directly on the grid at BME building Q, and were probably caused by a large three phase diode rectifier of a VFD used in the ventilation system of auditoriums. The difference after the series compensator is visible even on the waveforms, but the difference in the spectra are more spectacular.

Results with the described flicker compensation method can be seen in Fig. 6. Flicker was not available on the local grid, so approximately 2.5% of the fundamental voltage has been generated using another inverter with modified software. As visible in the spectra, the new method has worked well for both sidebands caused by 5Hz flicker, but was somewhat less successful in removing the upper sideband in case of 20Hz flicker.

3. Utilization, Efficiency Improvements

The first prototype of the device shown in Fig. 2. has been online since end of 2018 on a grid operated by E.ON. The device was equipped with a Teltonika RUT955 4G modem. This could be remotely accessed via VPN, and could provide a connection to the internal MODBUS interface connected to the inverter control micro-controllers. This functionality was also used for data logging throughout the full calendar year of 2020. The connection did not always work, probably because of poor cellular coverage and problems with the modem software.

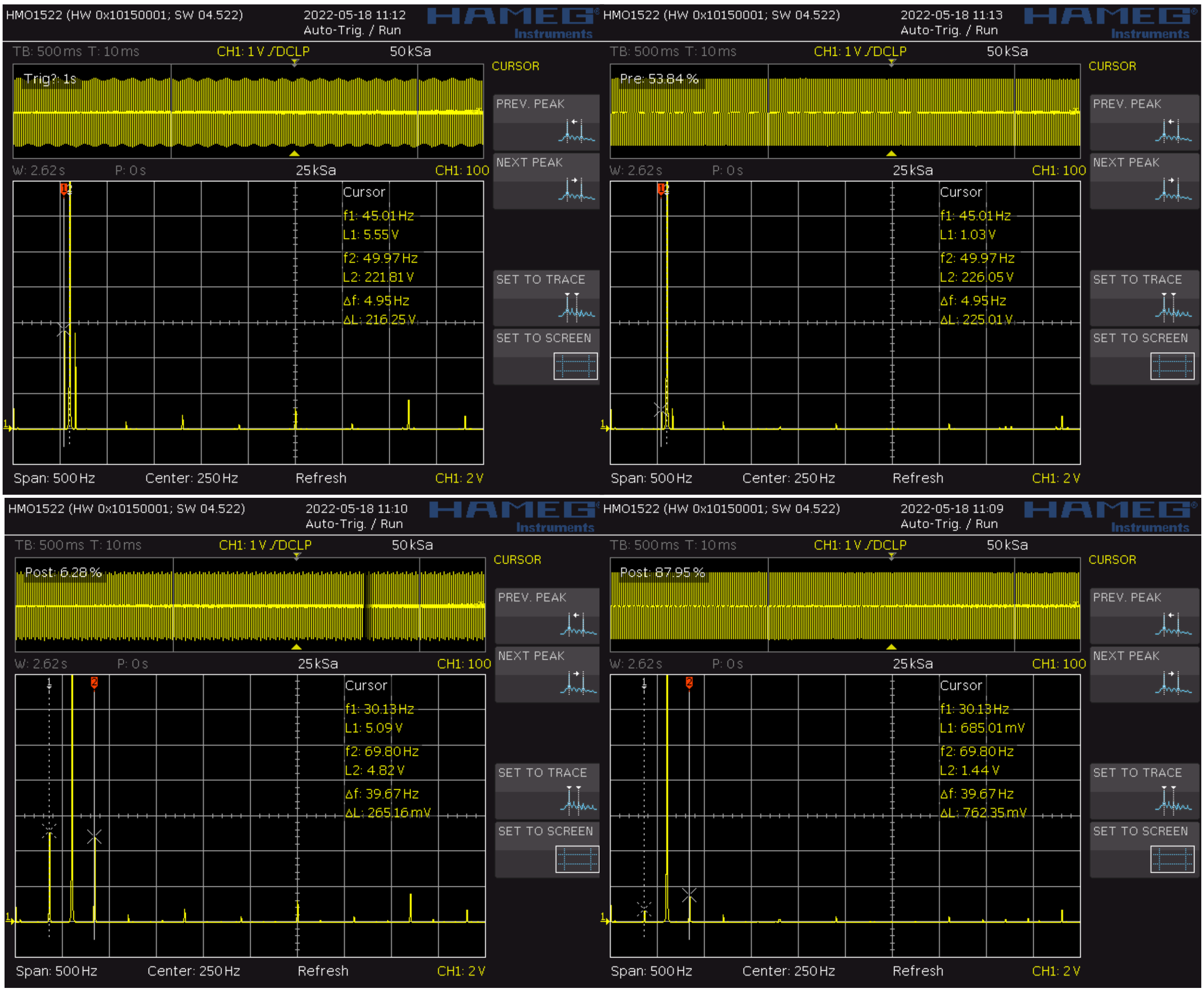

Fig. 6. Series compensation results for 5 Hz flicker (top) and 20 Hz flicker (bottom). Input figures: left, output figures: right

The available MODBUS registers were logged twice each minute when the link was operational. The histogram of Fig. 7 was generated from this data. The device has a rated power of 15 kW. The measured peak power during the year was less than 8 kW, and most of the load was less than 2 kW. The presence of negative load shows that the regulated branch has sometimes acted as a net generator due to high PV production, and the voltage had to be decreased by the DVR unit to avoid overvoltage and enable the operation of the PV inverters.

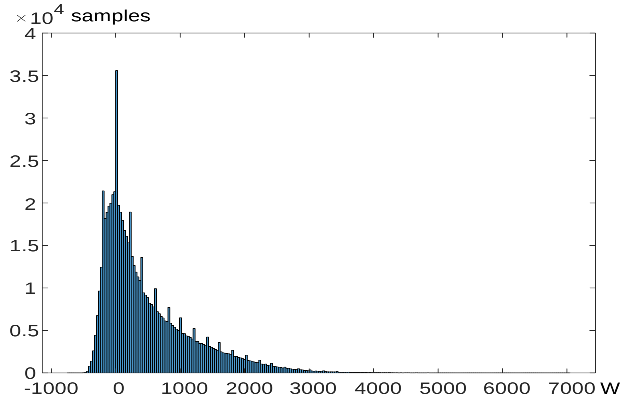

Fig.7. Actual recorded load data of a DVR-15 unit placed in the Hungarian village of Nagyvenyim for the full calendar year 2020

From the histogram it is visible that most of the operation is at partial load, mostly less than 10%. The efficiency of inverters is bad during such circumstances, because part of the losses (switching loss, inductor core loss) are constant. This means that efficiency could be improved by not using some parts of the converter. In modular systems this can be easily achieved by shutting off some of the individual modules [11]. This is not possible in single units, but two DVR specific methods have been identified.

A. Injection Phase Shut-Off

In the output inverter stage of DVRs it is possible to shut off one phase if the voltage to be injected is very small. In this case, shorting the injection transformers does not make much difference. To take advantage of this, a hysteresis band has been defined. If the fundamental RMS voltage is below the preset limit for at least 6 seconds, the injected voltage is slowly ramped down to zero. The duration of the ramp-down was set to 10 seconds. The realization of shorting has been done using the two center IGBTs of the NPC bridge. This has spared the switching and inductor core losses associated with the phase. In case the voltage to be injected is above the preset limit, a slow ramp-up is initiated. If the voltage to be injected increases even more, than a fast ramp-up of 100ms is initiated.

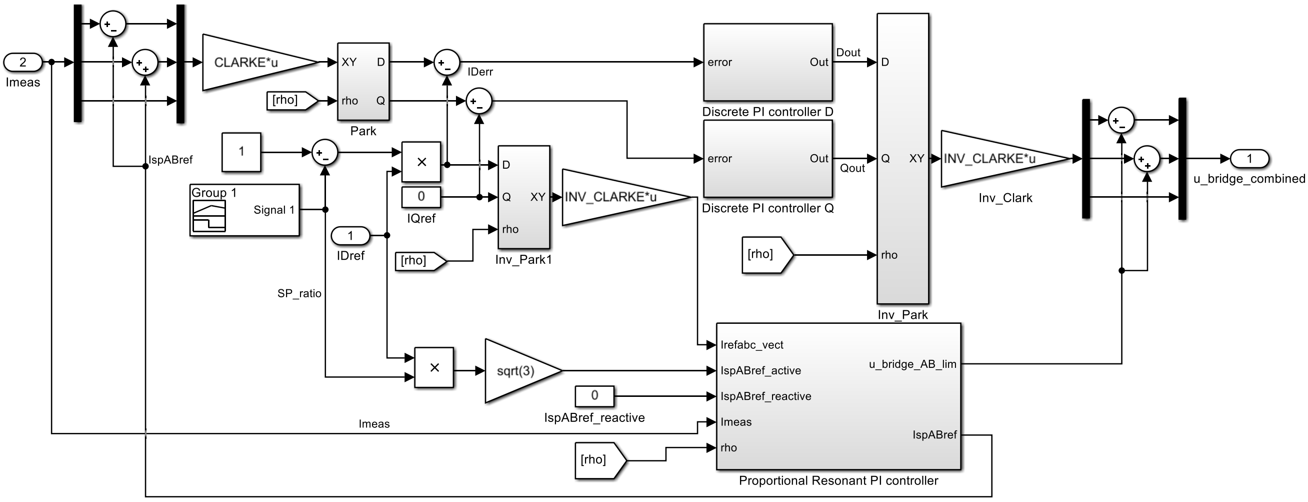

Fig. 8. Block diagram of 3-phase to 2-phase seamless transfer in Matlab Simulink

B. Active Rectifier Two-Phase Mode, Seamless Transfer

More losses can be spared by shutting off one phase leg in the three phase active rectifier stage. This way the active rectifier can continue operation as a single phase inverter operating from one line voltage at low to medium loads. In case of the DVR application, the unused phase can be chosen based on voltage. By not putting further load onto the already most problematic phase, the DVR can also help to increase the local symmetry of the grid.

The idea of phase shutoff in an active rectifier is only feasible if the transition can be executed while the converter is online, without any disruption to power flow. To achieve this, a seamless transfer method from 3-phase to 2-phase has been investigated. The new method performs the seamless transfer from a 3-phase vector current controller to a resonant PI controller [12]. The block diagram of this control can be seen in Fig. 8. The The resonant current controller has been added to the traditional vector control scheme in such a way, that its reference is subtracted from the measured currents fed into the vector controller, and its output is added to the output of the vector controller. This way the vector control is responsible for the symmetrical current component, and the resonant control is responsible for the single phase component. The ratio between single phase and three phase power can be set as a ratio in “SP_ratio”. A value of 0 commands completely symmetrical, while a value of 1 commands completely single phase only operation.

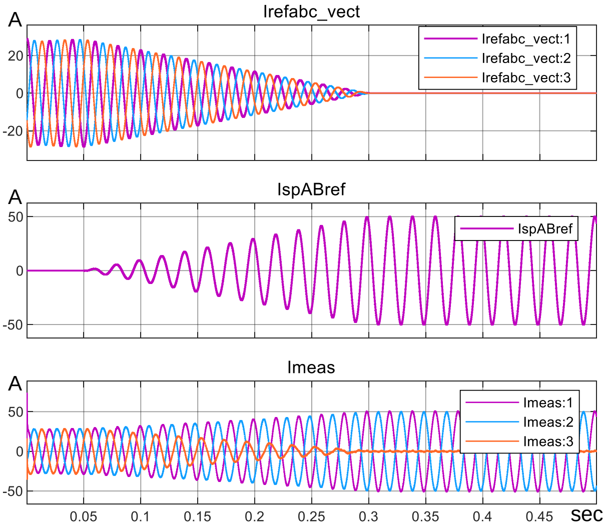

Fig.9. Simulation results with 3 to 2 phase seamless transfer

The new method has been tested for one phase configuration in Matlab Simulink simulation environment. Simulation results in Fig. 9 show the seamless transfer in operation. The transfer works in both directions, and its speed can be set as desired. The increase of current amplitude in the remaining two phases is required to maintain constant power. This clearly shows that the transfer to 2-phase is only recommended if the additional losses caused by the increase in current are less than the losses spared by not using one phase leg.

4. Conclusion

This paper describes the control algorithms used in a 15 kW low voltage series DVR prototype. Additional software functionalities include low order harmonic and flicker compensation performed via series voltage injection. These have been tested on a working prototype in laboratory environment. The operation of the prototype device inserted into an actual grid branch has then been logged for one full calendar year. From the collected data, it was shown that improving the efficiency at low loads is advantageous. Two new methods have been introduced to eliminate switching losses in one phase leg. A simple solution was used to disable series voltage injection if the voltage to be injected is very low. However, it has also been shown, that one phase leg of the active rectifier section can also be deactivated by using a novel seamless transfer scheme to switch from symmetrical three phase operation to single phase operation under load.

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