Design and Implementation of a Medium Voltage, High Power, High Frequency Four-Port Transformer

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***Abstract*—With the growth in penetration number and power level of renewable energy resources, the need for a compact and high efficient solid state transformer becomes more important. The aim of this paper is to design a compact solid state transformer for microgrid application. The proposed transformer has four ports integrated on a single common core. Thus, it can integrate different renewable energy resources and energy storage systems. The transformer is operating at 50kHz switching frequency, and each port can handle 25kW rated power. In this paper, the ports are chosen to represent a realistic industrial microgrid model consisting of grid, energy storage system, photovoltaic system, and load. The grid port is designed to operate at 4160V AC, while the other three ports operate at 400V. Moreover, the grid, energy storage, and photovoltaic ports are active ports with dual active bridge topologies, while the load port is a passive port with full bridge rectifier one. In this paper, an extensive and complete design and modeling of the entire solid state transformer is presented. The proposed design is first validated with simulation results, and then the proposed transformer is implemented. Some preliminary experimental tests are also performed and the obtained results are reported.**

Keywords— Finite element analysis, high frequency, high power, medium voltage, microgrid multi-port transformer, solid state transformer.

I. INTRODUCTION

From low scale applications such as LED drivers, battery chargers, and power supplies [1], to high scale ones like Electric Vehicles (EVs), wind turbines, and Photovoltaic (PV) systems, the world of power electronics is expanding in the industry. The traditional electrical power system is defined by three stages; power generation plants, transmission lines, and distribution system [2]. Typical low frequency transformers are used for electrical isolation between systems as well as to fulfill the voltage matching requirement. However, the 50/60Hz transformers are bulky and large in size and weight [3]. To minimize the gap between old power system and new microgrid concept, power electronic converters shall be utilized. The Solid State Transformer (SST) idea was born for this application. It is defined as a high/medium frequency transformer implemented with a power converter. This will have a direct positive impact on the size, compactness, and power density compared to the traditional low frequency transformers.

Recent developments on advanced magnetic materials with low power loss and high saturation flux density as well as high power-high frequency switching devices made it possible to design high efficiency high power density SSTs [4]-[6]. Many studies have been projected lately on SST design [7]-[13]. However, most of these studies are on conventional two-winding transformers. The significant increase in the number of Distributed Generations (DGs) and the importance of smart grid and microgrid concepts has dictated the need for a single compact component integrating multiple sources. This triggered the idea of a Multi-Port Solid State Transformer (MPSST). Few articles and research work have been directed towards this concept [13]-[19].

Generally, Dual Active Bridge (DAB) converters are used at each port of the converter. The DAB converters used in SST applications use the transformers' leakage inductance as converter inductor. This eliminates the additional inductor requirement and provides a reduction in total size and loss values. The leakage inductance value depends on the core geometry, winding placement, and coupling factors, hence, the transformer model gets more complex and challenging to design. In addition to parameters such as efficiency, energy density, cost, parasitic capacitance, insulation, etc., requirements on the leakage inductance must be also satisfied. In MPSST design, since many windings are integrated, design of the transformer and obtaining desired leakage inductance value is more complex [7]. Besides, for MV levels, the insulation requirements increase the design complexity and difficulty.

In DAB converters, the power flow from one port to another is controlled via the phase-shift. However, in MPSST applications, a change in phase-shift in one converter affects the power flows among all other ports. Thus, increase in number of ports increases the control complexity. Therefore, most of the MPSST studies have focused on three-port systems [19]. In [16], design of a 10kW/port four-port transformer for the SST application is presented. Possible applications of MPSST and volt-VAR control in future distribution systems is also proposed in [15]. In [19] and [20], control schemes are

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presented for four-port SST. However, all the ports in these studies are designed to operate at low voltage level.

Integration of multiple renewable energy resources will be a key design milestone for future distribution systems. In order to eliminate the use of multiple converters and two-ports transformers, and hence achieve electrical isolation and system compactness, a solid state transformer that connects four-ports on a single common transformer core will be presented and discussed in this paper. This transformer can be utilized in different microgrid systems such as a stand-alone facility, residential houses, commercial buildings, remote oil & gas fields rigs, etc. This study targets a rated operating power of 25kW for each port. The ports can represent different distribution generations such as wind turbine, PV system, etc. In this paper, the first port represents a 4160V AC grid, while the other three ports operate at 400V representing the battery based Energy Storage (ES) system, the PV system, and the load. The aim is to prove the operation and functionality of the MV MPSST concept, therefore, it is assumed that 7.2kV DC (corresponding to 4160V AC) and three 400V DC buses are present for the grid and the three ports, respectively. Three active DAB converters operating at 50kHz switching frequency are implemented for the grid, PV and ES ports, while a passive full bridge rectifier is designed for the load side. Moreover, the grid and ES ports are designed to be bi-directional in-order to either provide or draw power, while the PV and load ports are uni-directional. Fig. 1 below illustrates and summarizes the discussed system. In this study, complete design of this four-port transformer is given.

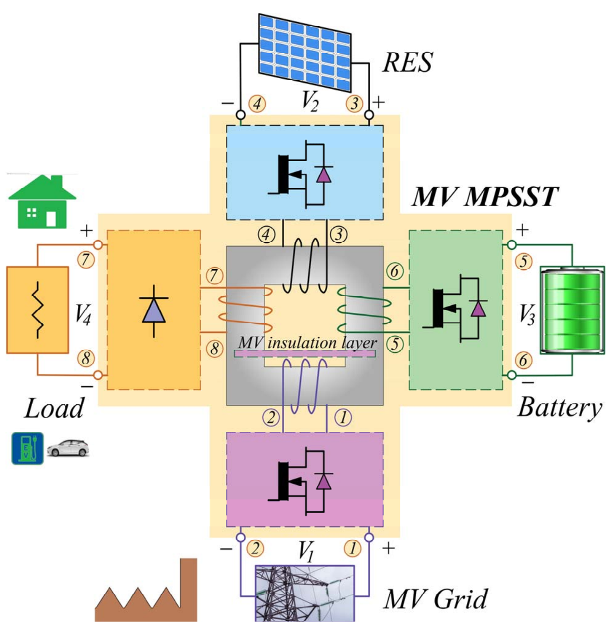


Figure 1: The four port solid state transformer.

The complexity of this concept lies behind two main factors, namely; four-winding 50kHz transformer design and power flow control across the four ports. This paper targets the first one. Transformer design challenge includes handful dynamics and tradeoffs that should be accommodated for. A thorough analysis has been conducted to study the needed core material/shape/size/volume, windings placement/configuration/ number of turns/parasitic capacitances, insulation level, leakage/magnetizing inductances, transformer losses, efficiency, and power density. The work has been tackled by a Finite Element Analysis (FEA) modeling and simulation. The designed transformer model is validated with ANSYS-Maxwell and ANSYS-Simplorer simulation and co-simulation studies. Then, the designed MPSST is implemented, and experimental tests are performed on the MV MPSST prototype for results validation and proof of concept. Afterwards, the system prototype along with its experimental testing results will be presented.

Table 1: Core Material Comparison.

Core Material	Flux Density	Power Loss	Permeability	Availability	Cost
Silicon steel	☑	☒	☑	☑	☑
Amorphous	☑	☒	☑	☑	☒
Ferrite	☑	☑	☑	☑	☑
Nanocrystalline	☑	☒	☑	☒	☒

Table 2: Ferrite 3C94 Characteristics.

Symbol	Conditions	Value	Unit
μ_i	25 ºC; ≤10kHz; 0.25mT	2300 ±20%	
μ_a	100 ºC; 25kHz; 200mT	5500 ±25%	
B	25 ºC; 10kHz; 1200 A/m 100 ºC; 10kHz; 1200 A/m	≈ 470 ≈ 380	mT
Pv	100 ºC; 100kHz; 100 mT 100 ºC; 100kHz; 200 mT	≈ 50 ≈ 350	kW/m³
p	DC, 25 ºC	≈ 5	Ωm
Tc		≥ 220	ºC
Density		≈ 4800	kg/m³

II. Transformer Design

The industrial commonly used transformer core material are silicon steel, Amorphous, Ferrite, and Nanocrystalline. The targeted application dictates the use of optimal material for a 25kW/port four-ports transformer operating at 50kHz switching frequency. A literature review has been carried out in-order to compare the material characteristics at these operating conditions and ultimately choose the optimal material. Table 1 will serve as a summary for the different material main attributes for the MV MPSST application.

Analyzing the above table shows that ferrite and nanocrystalline are the best options to go with. However, it is recommended not operate nanocrystalline in applications exceeding 10-20kHz for its power loss drawback. Therefore, ferrite will be considered as the transformer core material for this paper. Ferrite 3C94 [21] which is used for power transformers up-to 0.3MHz has been selected based on its specifications that suits the MV MPSST application. Table 2 encapsulates its main parameters and characteristics.

The mechanical design of the core is crucial since it is directly related to the power density, cross-sectional area, leakage inductance, volume and hence, transformer compactness. One can argue that minimizing the leakage inductance factor is the top important factor to take into consideration. The core-shape and the shell-type configurations have been compared on a 330kW 50kHz two-port transformer [22]. It has been proven that shell-type provides the topmost efficient performance along with the minimum leakage inductance and smooth power flow. Consequently, shell-type transformer configuration has been selected for the proposed MV MPSST application. As a result, the four windings will be placed on top of each other in the middle leg of the shell-type transformer in order to maximize the coupling coefficient.

Mathematical calculations that will set a first transformer design stage have to be derived. A MATLAB code is implemented to determine the optimal parameters to be a starting point for the modeling stage. The set of general transformer design equations used in MATLAB code are given below:

$$v(t) = N\frac{d\emptyset(t)}{dt} = NA_C\frac{dB(t)}{dt} v(t) = \quad (1)$$

$$A_{wire} = \frac{1}{J} \quad (2)$$

$$P_{Core} = k_{ref}B^{\beta}f^{\alpha} \quad (3)$$

$$P_{copper} = \left(1 + \alpha(T_c - 20)\right)x1.7x10^{-8} \quad (4)$$

$$P_{sw} = \begin{pmatrix} -1.5432099 \cdot 10^{-8}I^2 + 4.72222 \cdot 10^{-5}I \\ +2.222 \cdot 10^{-3} \end{pmatrix} f_s \quad (5)$$

$$B_m = \frac{V}{4xfxNxA_C} \quad (6)$$

$$A_P = A_C W_a = \frac{S}{K_f K_{cu} B_m f J} 10^4 \quad (7)$$

$$N = \frac{V}{K_f A_C B_m f}\left(1 - \frac{T_d}{\pi}\right) \quad (8)$$

where, V represents the induced voltage, N is the number of turns, A_{wire} is the wire cross-sectional area, I is the rated current, J is the current density, P_{core} is the core losses, k_{ref}, β and α are core coefficients extracted from the material datasheet, P_{copper} is the copper losses, α is the wire coefficient, T_c is the core temperature, P_{sw} is switching losses, f_s is the switching frequency, B_m is the maximum flux density, A_c is the core cross-sectional area, A_p is the product area, W_a is the window area, S is the rated power, K_f is the waveform coefficient, K_{cu} is the window utilization factor, and T_d is the dead-time for switches.

After going through the market available ferrite 3C94 shapes, 4xU93/76/30mm (height/width/depth) has been concluded to form one layer of shell-type core with 186/152/30mm dimension [21]. Besides, to reduce the high proximity and skin effects at high switching frequencies, Litz wire is being deployed as the windings wires. The rated current values of 3.42A and 62.5A for MV port and LV ports dictate the use of 16AWG and 4AWG wires, respectively. After a mechanical wiring placement study, it was concluded that using 2x8AWG wires for each LV winding turn is more efficient and compact than using a 4AWG wire. Moreover, it was determined that wrapping the LV wires together will optimize the coupling coefficient. Plugging the aforementioned design parameters into the optimization MATLAB code has led to the following analysis. In Fig. 2, the variations of B_m, core loss (P_c), winding loss (P_w), sum of core and winding losses (transformer losses, P_{tr}), sum of transformer and switching losses (total losses, P_t), and core and copper weight, have been plotted and demonstrated with respect to A_c and N. Analyzing the plots reveal that for the LV ports, A_c and N being in the range of 34.08-51.12cm^2 and 6-12, respectively, will result in a high transformer efficiency. However, it was noticed that going above 9 turns will increase the core and copper volumes, and in-return, causes an increase in the cost and a reduction in the power density. These results gave a good building block information and starting point for the MPSST design.

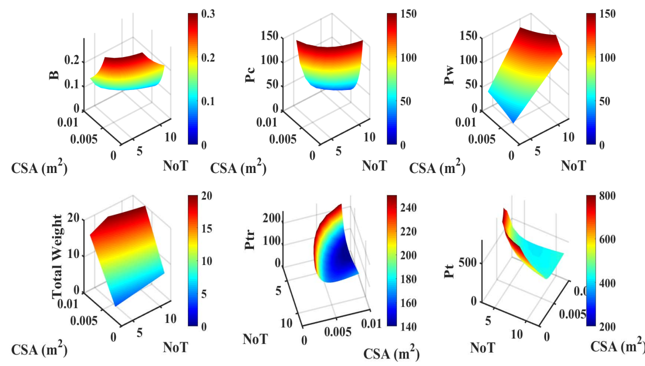


Figure 2: Results for theoretical calculations.

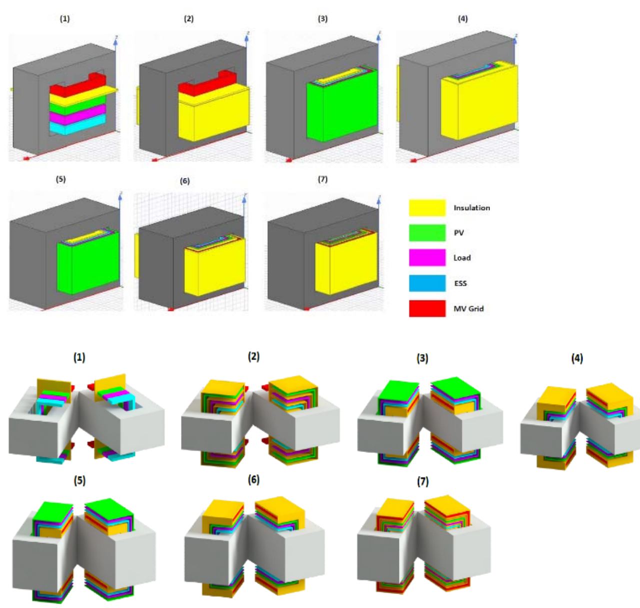


Figure 3: Investigated MV MPSST design models: Side View & Cut-out.

The insulation standard requirement for a dry-type transformer is described in IEEE Std. C.57.12.01 and IEEE Std. C57.124. The requirement describes how to make Basic Impulse Lightning (BIL) and partial discharge tests. According to these standards, BIL test voltage for this MV MPSST transformer shall be at 30kV. For partial discharge testing, the operating voltage should be increased 1.8-times for a 30-seconds duration, then followed by an increase of 1.3-

times for 3-minutes timeframe. At the end of the test, the partial discharge level should be less than 10pC for solid cast winding transformer. In-order to ensure proper insulation between windings, 10kV AC red single polyurethane-nylon (MW80-C)

Table 3: Design Models Dimensions.

Model No.	1	2	3	4	5	6	7
Shapes Used	8U	8U	8U	8U	12U	12U	12U
Ac (cm^2)	34.1	34.1	34.1	34.1	51.1	51.1	51.1
Volume (cm^3)	1122	1122	1122	1122	1683	1683	1683

has been used as cables insulation jackets. Moreover, multilayer Kapton adhesive taped on Nomex 818 sheets were inserted between each winding layer. These sheets reached more than 32kV of insulation level. Several models have been simulated with different core sizes (34.08-51.12 cm2), number of turns (6-9), and winding arrangements as shown in Fig. 3 and Table 3. Each design is modelled in ANSYS-Maxwell-3D, and then co-simulated with a power electronic converter modelled in ANSYS-Simplorer. The transformer is tested for different operating conditions with different phase-shift angles. It should be noted that ANSYS just gives the self and mutual inductance matrix between the four ports and does not calculate the leakage and magnetizing inductance values. Therefore, a systematic and theoretical mathematical derivation has been carried out in-order to calculate these inductances values. The MPSST equivalent circuit was derived and the winding arrangements have been taken into consideration in-order to calculate the leakage inductance for all the models of Fig. 3. This mathematical long derivation is not the purpose of this paper and thus it will not be presented.

III. SIMULATION RESULTS

Simulation of the complete system by linking the Maxwell-3D model (physics and magnetics of the transformer) along with Simplorer circuit (power electronics circuit) will result in a complete and realistic simulation of the entire MV MPSST system. After the evaluation of the possible design models for the proposed MV MPPST (Fig. 3), Maxwell-3D/ Simplorer co-simulation studies are carried out (Fig. 4). The ports voltages of the system are 7.2kVDC for MV grid port and 400VDC for energy storage, PV, and load ports. The simulation is carried out at 50kHz switching frequency and at full load to deliver 25kW to the load port. The duty cycle of the PWM signals are kept constant at 50% and power control is obtained by controlling the phase-shift angles among the H-bridge converters. The obtained results from the simulation studies are presented in Table 4 for each design model. Here, core shape, effective cross-sectional area, volume, transformer losses, and efficiency are given for each model. It is seen that Model 7 provides the lowest leakage inductance with the highest efficiency level. The flux distribution of this model is given in Fig. 5. It is seen that the maximum flux density is around 0.17T which is below the design target limit that is defined by ferrite material specifications. The detailed parameters of the selected optimal model are given in Table 5. As seen from the results, the total loss of the transformer is obtained as 73.4W, and then the efficiency of the transformer is calculated as 99.7%.

Fig. 6 shows the ports currents and voltages waveforms obtained from ANSYS-Maxwell-3D/ANSYS-Simplorer co-simulation results with Model-7. As can be seen from the figure, while the PV and grid port currents are in one direction, the load and energy storage port currents are in reverse direction. At this instant, the grid and PV ports are delivering power to the load and energy storage ports.

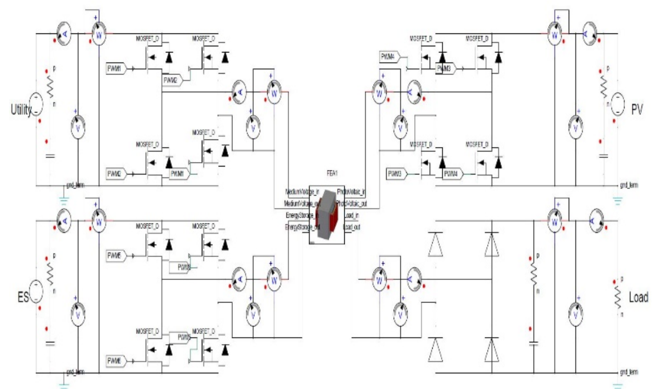


Figure 4: Maxwell-3D/Simplorer Transient-Transient Co-Simulation model.

Table 4: Design Models Simulation Results.

Model No.		1	2	3	4	5	6	7
B_{max} (T)		0.26	0.28	0.50	0.26	0.32	0.2	0.17
Parasitic Cap. (pF)	ES	20.7	30.1	109	74.7	126	142	92.3
	Load	30.5	41.4	191	141	219	169	171
	Grid	8.3	9.9	44.7	52.5	54.6	61.6	70.4
	PV	19	24.6	130	122	151	91.4	151
Leakage Ind. (µH)	ES	5.9	2.7	905	0.8	905	0.7	1.2
	Load	6.5	2.6	905	0.7	905	0.8	0.8
	Grid	7.9	6.6	906	0.8	906	1.0	0.4
	PV	8.3	3.0	162	0.6	162	1.0	0.6
Magnetizing Ind. (µH)		1812	1795	906	1847	906	2735	6065
Losses (W)	Total	91.7	133	246	383	117	375	73.4
Efficiency (%)		99.6	99.5	99	98.5	99.5	98.5	99.7

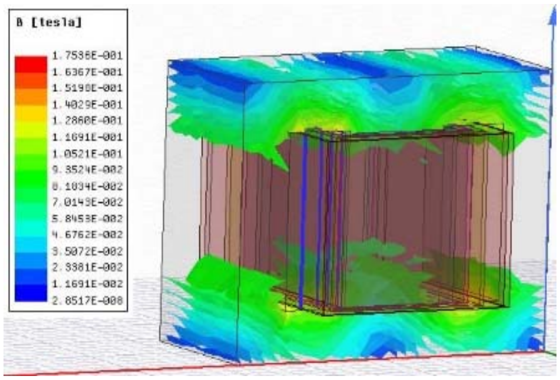
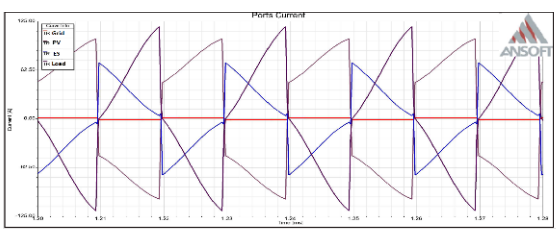


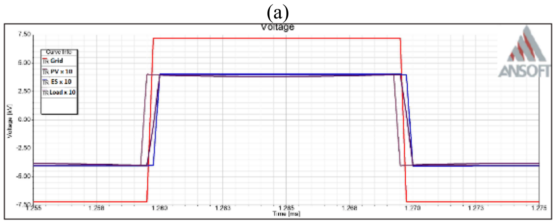
Figure 5: Model 7 Flux Distribution.

Table 5: Optimal Design Parameters.

Parameter		Value
No. of Turns		9/9/9/162
Litz Wire (AWG)		2x8/2x8/2x8/16
B_{max} (T)		0.175
Leakage Ind. (μH)	ES	1.254
	Load	0.838
	Grid	0.448
	PV	0.604
Magnetizing Inductance (μH)		6064.900
Transformer Losses (W)		73.4
Efficiency (%)		99.7
Effective Area (cm^2)		51.120
Core Volume (cm^3)		1683



(a)



(b)

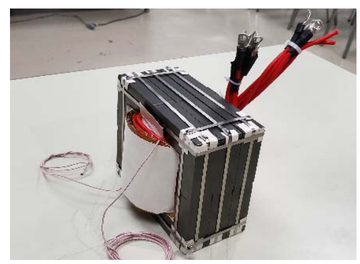
Figure 6: Simulation results for Model-7 a) Waveforms of port currents, b) Waveforms of port voltages.

IV. Experimental Setup and Test Results

After desired specifications are achieved for simulation studies, the designed transformer is implemented. In Fig. 7(a), the core and the insulation layer is shown. As seen from the figure, 4 U cores are used to generate one layer of the core, and the core compose of 3 layers. Then, windings are placed on the core. All three low voltage port windings are wrapped together. The picture of the transformer is shown in Fig. 7(b).

To test the transformer, three DAB converters are designed and implemented. SiC MOSFETs are employed in converter circuits. Since the MV port is considered as the load port (for testing purposes), a MV bridge rectifier is implemented by using SiC Diodes. MV load port is loaded with resistor bank specially designed for 7.2kV. The experimental set-up implemented to test the designed MV four-port MPSST is depicted in Fig. 8. All MOSFET modules and drivers, control board, signal conditioning board, MV four-port transformer and MV rectifier can be seen from the figure.

(a)



(b)

Figure 7. a) The core of the designed four-port transformer, b) The designed transformer.

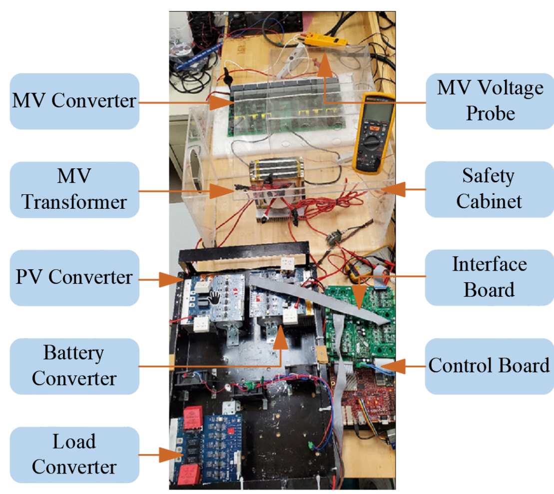


Figure 8. MV four-port transformer test set-up.

Some preliminary test studies are performed with the implemented system. In Fig. 9, the port voltages and currents are given.

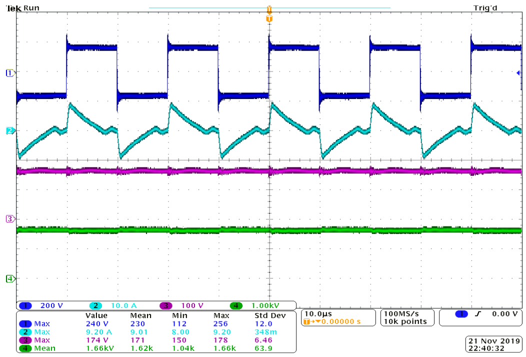


Figure 9. Port voltage and current waveforms of designed four-port solid state transformer (Port 4 DC load voltage attenuation factor is x0.5 factor, hence, the load voltage shown in the waveform shall be multiplied by a factor of 2, i.e. voltage of port 4 is around 3.6kV).

V. Conclusion

In this study, a four-port SST which is capable of connecting four different load or source ports together is designed for microgrid applications. One port of the transformer is designed to be operate at MV (compatible with 4.16kV AC voltage). Different design models are considered and optimal design is obtained. The obtain design model simulated and with FEA software. 99.7% transformer efficiency is obtained. Then, the designed transformer is implemented. In addition, to test the transformer, a test set-up including LV full-bridge converters, MV rectifier is implemented. Some preliminary test results are also presented.

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