Zhabelova, G., A. Yavarian, V. Vyatkin and A.Q. Huang, "Data center energy efficiency and power quality: an alternative approach with solid state transformer", in *41st Annual conference of the IEEE Industrial Electronics Society, IECON 2015*. 2015: Yokohama, Japan, *submitted*

Data center energy efficiency and power quality: an alternative approach with solid state transformer

Gulnara Zhabelova[1], Alireza Yavarian[1], Valeriy Vyatkin[1,2]
[1]Department of Computer Science, Electrical and Space Engineering
Lulea University of Technology, 971 87 Lulea, Sweden
[2]Department of Electrical Engineering and Automation, Aalto University, 02150, Helsinki, Finland
Lulea, Sweden

Alex Q. Huang
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC 27695, USA

***Abstract*— Data center evolved to become large power consumers. Its supporting infrastructure, such as cooling and power distribution, consumes resources e.g. electric power and money. In fact, most money is spent on power conditioning and cooling systems. Therefore, the efficiency of data center and power quality are important topics and can be addressed by careful design. There is a need for research into application of innovative design and state-of-the-art technology for optimizing power supply in data centers. The paper investigates the potential of a state-of-the-art technology such as solid state transformer (SST). The simulation proves that SST has potential to improve operational efficiency. SST shows better control of voltage, current and reactive power of the facility, eliminating need for additional devices such as power conditioners and reducing power loss. These results lead to the next stage of the project that involves developing an optimal data center design with SST and investigating data center potential in demand response applications.**

Keywords—data center, SST, solid state trasnformer, power quality, data center efficiency, PUE, power loss, voltage and current fluctuations, active power, reactive power.

I. INTRODUCTION (*HEADING 1*)

Large data centres are a new and growing industry, in particular in Northern Sweden. They are also large industrial electric energy consumers. For example, Facebook in Luleå consumes the comparable amount of energy (100MW) to the SSAB coking steel plant that previously has been the largest energy consumer in the region. In the US datacentres are responsible for more than 2% of the US total electricity usage [1].

Data center is not just a collection of servers; it needs support of a complex infrastructure providing power supply, cooling system and maintenance. This infrastructure consumes resources such as electric power and money, and although it is crucial to data center operation, it does not directly produce the useful work of such as computing. The most money is spent on either power conditioning or on cooling systems [2]. Therefore efficiency of a data center is an important topic.

There are several sources of energy inefficiency. The inefficiency of transformers is less than 0.5% [2] and can contribute towards 2% of the power losses [3]. Uninterruptible power supplies (UPS) is the source of the most conversion losses, its typical efficiency is 88-94%. And there is a considerable amount of energy can be lost in the long cables delivering low voltage power (110 or 220 V) to the racks. Typically 1-3% is lost in these cables [2]. The energy efficiency of data centers can be improved by careful design.

Figure 1 shows conventional data center power supply chain and improved system designed by Facebook Open compute project [4]. Power losses in typical infrastructure can accumulate up to 27%. Facebook has made several design choices in electrical system and removed main sources of power losses. This resulted in highly efficient electrical system and small failure domain [4][3]. The total power losses were reduced to 7.5%. However, additional measures need to be taken to protect servers from unconditioned utility power.

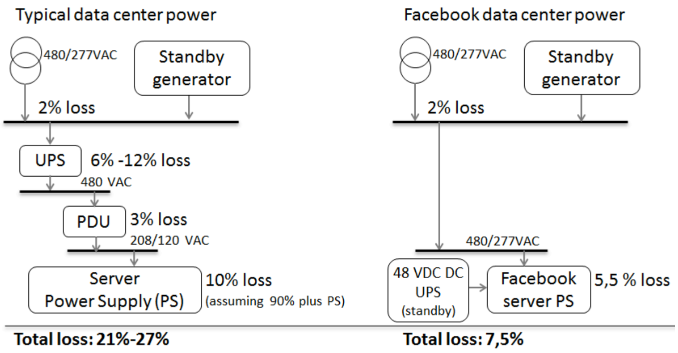

Figure 1. Facebook data center design innovation – electrical system [3].

Facebook experience demonstrates that it is possible to improve efficiency of data centers by applying alternative designs. Facebook approach concentrates on the design of the internal structure of a data center. Yet, there is potential for various designs considering point of connection to the regional grid.

There is a need for research into application of innovative design and state-of-the-art technology for optimizing power supply in data centers.

Another important issue in the data center is power quality. The IT equipment, such as servers, network devices and storage, is sensitive to the power quality. Therefore, the power supplied by the utility has to be conditioned i.e "cleared" from the noise e.g. variations in voltage, surges and other electrical disturbances [5]. These electrical impurities can disrupt and even damage sensitive electronic equipment. Data center deal with this by installing so called "power conditioners" devices. However, this results in the increased cost of installation and operation of the data center, additional equipment needs maintained.

This paper focuses on two issues discussed above: power losses and power quality in the data center power infrastructure.

The paper investigates potential of a state-of-the-art technology such as solid state transformer (SST) to increase efficiency in data centers by improving power quality, eliminating need for additional devices such as power conditioners and reducing power losses.

SST is a novel digitally controlled power-electronics technology aiming at replacement of the traditional transformers. SST supports both DC and AC power [6], and therefore is suitable for data center power infrastructure design in DC, which is proven to be more efficient than AC based systems due to conversion losses. There is a potential to increase efficiency of the data center by reducing energy loss in the power infrastructure when introducing SST. Moreover, due to internal AC/DC/AC conversion, SST filters electrical impurities in the incoming power. Therefore, SST can provide a data center with better power quality by inherently shielding sensitive loads from unconditioned utility power. This can simplify electrical infrastructure of a data center.

However, before SST can be adopted by the datacentres industry, a fundamental question need to be answered: how SST can help in increasing energy efficiency of datacentres?

The paper described the following contribution of this work:

- We prove that SST has potential to improve operational efficiency of the data center. We show the impact of having an SST in the power infrastructure of a data center improves power quality.
- We demonstrated this by building models of data centers with traditional power infrastructure and with SST (section III). We conducted experiments under various conditions described in section IV and analyzed results comparing performance of both models (Section IV).

In order to appreciate the impact of SST on the data center power infrastructure, one needs to understand the fundamental concept, the device has been built on. Next section will provide a short overview of SST and its architecture.

II. Solid State Transformer: Short Overview

Solid state transformer is developed by the NSF funded Future Renewable Electric Energy Delivery and Management (FREEDM) system center [11].

SST is a semiconductor based transformer with main function of stepping down the voltage [11]. However, design of SST has extended the transformer functionality and enabled SST with capabilities of power exchange and energy routing, i.e. it allows for bidirectional energy flow. [11].

A simplified functional diagram of SST is shown in Figure 2. SST typically includes three cascaded converters: high voltage AC to DC power conversion; high frequency high voltage DC to low voltage DC converter and low voltage DC to AC conversion [11][12][13]. Last two stages produce regulated DC and AC busses correspondingly. The rectifier stage of the SST allows an independent control of active and reactive power. That is, given a battery is connected to a low voltage DC link, one can send a control command with desired active and reactive power, and SST will try to generate requested power, automatically involving connected battery.

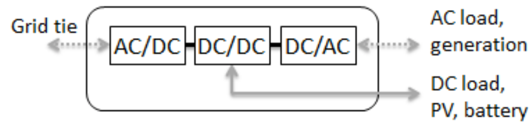

Figure 2. Solid state transformer functional configuration [11].

This structure allows input and output power factors to be independent and separates the input (grid) side parameters such as voltage and frequency from the low voltage output. This feature is very important, as it improves power quality and strengthens the system stability by decoupling low voltage side from the grid [11]. Existing designs of SST have already proven to provide power factor correction, voltage sag restoration and fault current limiting [11]. Moreover, SST operates under the unit factor condition, and therefore can exhibit to the grid a behavior of purely resistive load or purely active power generation [11]. Furthermore, SST delivers very fast response time, which is important for power system reliability.

More detailed description of SST is presented in the original papers [11][12][13].

The SST provides much more control options and functions that go beyond of functionality of the typical distribution transformer. Therefore, it is important to understand potential of the new technologies such as SST in improving operational efficiency of the data centre and discovering new opportunities.

This paper presents an attempt to understand effect of SST application in data center power infrastructure. Next section will describe simulation models what were developed for this purpose.

III. Simulation Models

This section described two models of data center: a traditional with AC power infrastructure and model with integrated SST.

The aim of the simulation is to see the impact of SST and compare power characteristics of the data center under various conditions: changing load capacity; utility power failure and transition to standby generator.

The power infrastructure of a data center consists of several main building blocks, which is common for all data center such as utility transformer, automatic transfer switch (ATS), switchgear, uninterruptible power supply (UPS), backup generator, power distribution units (PDU), cooling system and servers. The arrangement of these components into

Zhabelova, G., A. Yavarian, V. Vyatkin and A.Q. Huang, "Data center energy efficiency and power quality: an alternative approach with solid state transformer", in *41st Annual conference of the IEEE Industrial Electronics Society, IECON 2015*. 2015: Yokohama, Japan, *submitted*

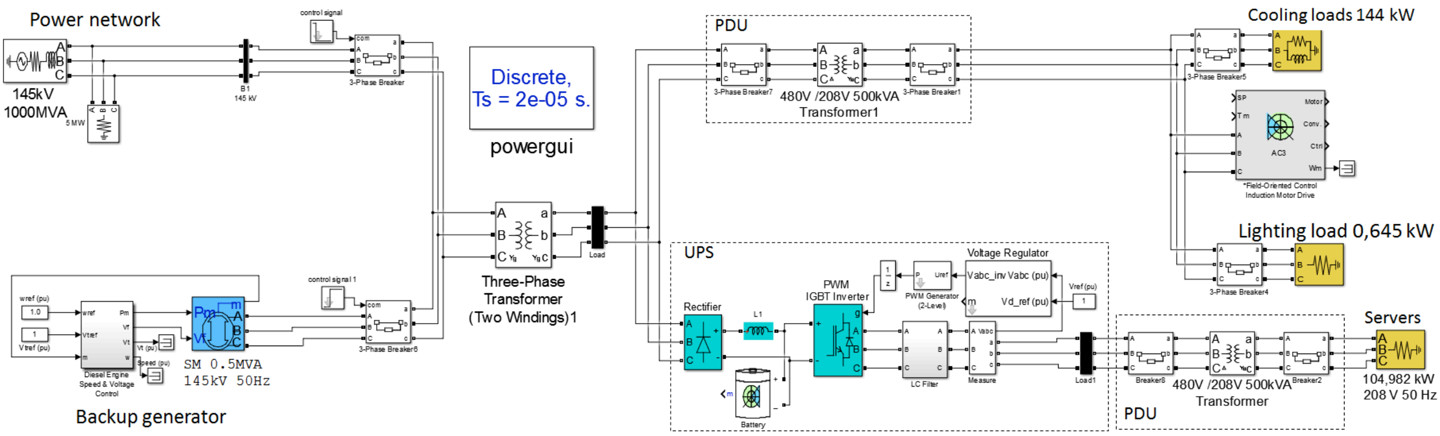

Figure 3. Model of a typical data center.

functional power system is different for various performance requirements of various data center

Figure 3 shows model of a typical data center. The model consists of a power source (a utility), ATS, backup generator, UPS, PDU and loads. UPS ensures constant power supply while data center transfers to the backup generation when utility fails. It takes several seconds to minutes for generator to start up. The power is stepped down and supplied to the loads through the power transformer. There are three categories of loads considered: critical load, essential load and non-essential load. The servers, storages and all IT equipment are considered as critical loads.

The *critical load* needs to be protected and is supplied by UPS via PDU. The total capacity of critical loads is 104.95 kW. This power capacity was estimated using HP Power advisor calculator [9], by modeling 6 racks of BL460c Gen8 blade servers and 4 racks of network and storage devices. Critical load changes during the day, as the server utilization and load on other IT equipment follows the end-users behavior pattern.

The lighting loads have fixed power; they constitute *non-essential loads* and connected to the substation via PDU. The size of lighting loads is about 0.645 kW, calculated according to the method described in [10]. The motor of fans and pumps of cooling system are modeled as *essential loads*; a 72 kW induction motor is considered as the aggregated essential load and another 72 kW is modeled as equivalent RLC load.

Figure 4 shows data center with integrated SST in to the power infrastructure. In this model UPS and PDU were eliminated from the design and SST is inserted instead. Ideally the SST would substitute utility transformer where utility power enters the facility. This is the next step of this project and at this stage SST is used at lower voltage inside of the data center infrastructure. UPS is substituted by the DC battery set directly connected to the critical load, inspired by the Open Compute design [4]. All model parameters remain the same.

The Table 1summarizes the parameters of the data center model.

TABLE 1. DATA CENTER PARAMETERS.

Item	Capacity
Critical load	105 kW
Lighting	0.645 kW
Cooling load (induction motor)	72 kW
Relief load (RLC load)	72 kW
Standby generator set	500 kVA
UPS	128 kW

In order to analyze impact of SST, both models were simulated using the same scenario, described in the next section. Simulation results were also compared and analyzed in next section.

IV. SIMULATION AND RESULTS

This section describes three scenarios: changing load capacity and islanding operation. While the dynamic IT load is fairly common in data centers, an islanding operation is an

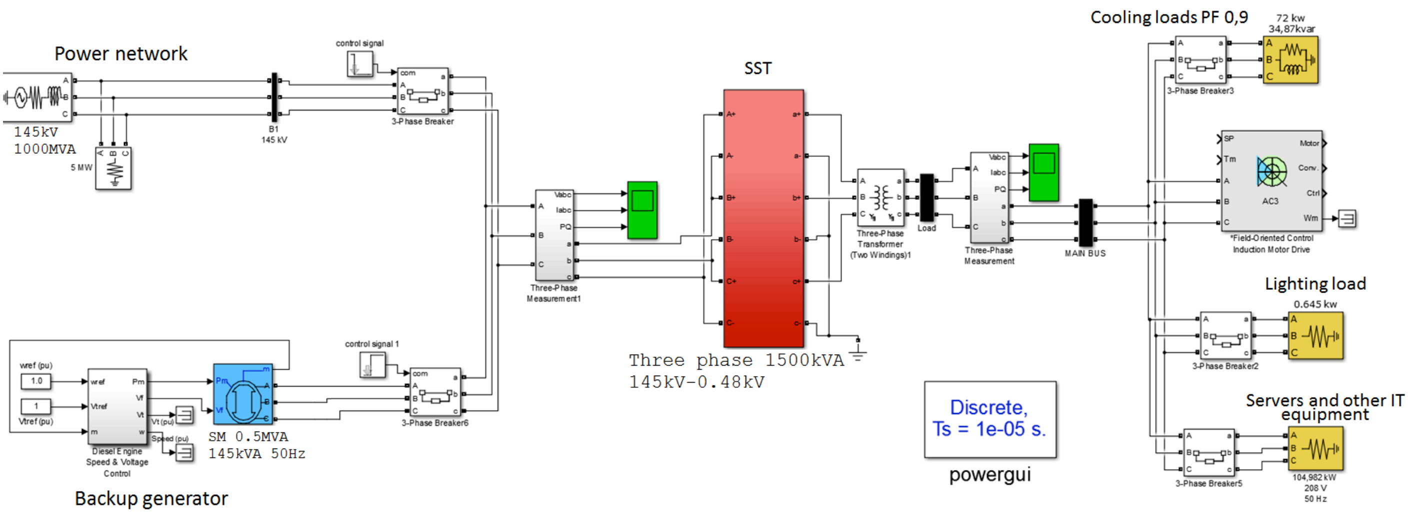

Figure 4. Model of a data center with SST in its power infrastructure.

emergency action plan. In islanding operation, data center is switched to power supply from backup generation as a reaction to power loss from utility (e.g. fault in the distribution network). In typical data center, the non-critical equipment is directly supplied with the unconditioned utility power, exposing devices to voltage, current and power fluctuations. In the data center configuration with SST, all loads are supplied via SST (Figure 4), improving power quality for whole infrastructure including fan motors, thus reducing power losses.

The simulation will show an impact of SST on the stability of electrical parameters and the power loss resultant from power fluctuations in data center power infrastructure.

A. Increasing critical load

The simulation scenario starts with normal operation of the data center, power supplied by main utility, and critical load is at its 25% capacity. Then at t=0.15 sec., critical load is increased to 50% of its capacity to simulate increased IT load. This causes voltage sag and an increase in current. Current stabilizes around new value; however, voltage should be kept at the same level 480V.

Simulation results of both models are shown in Figure 5. Thanks to the SST native voltage control, after the transient period (0.15 sec – 1.175 sec), voltage is stabilized at the near nominal level. Typical data center infrastructure allows voltage to fluctuate even after the transient period with the relatively larger magnitude. Figure 6 shows that the current increased fast and in two stages. The second current surge at 0.2 sec. has been effectively dampened by SST. In both models, current continuous to rise, but model with SST shows smoother climb. Increase in critical load causes increase and fluctuations in active and reactive power as shown in Figure 7 and Figure 8. SST performed better in stabilizing both active and reactive power. SST is capable to control reactive power better than the active power (Figure 8), keeping it close to pre-transient value and dampening the variations.

The SST is capable to damp the harmonics of power system that causes voltage instability of voltage. Voltage instability affects the power loss in the infrastructure and the lifetime of IT equipment. Maintaining voltage quality is the one of the goals of power system operation.

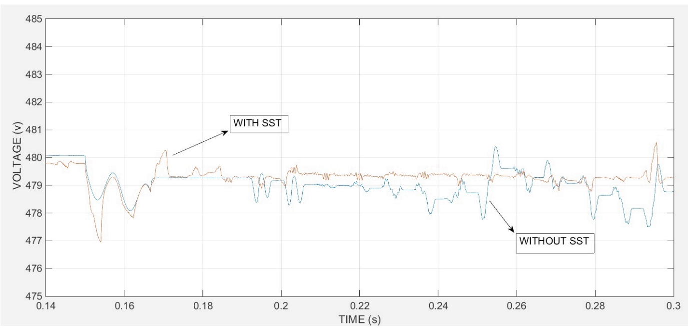

Figure 5. Data center voltage under increased critical load.

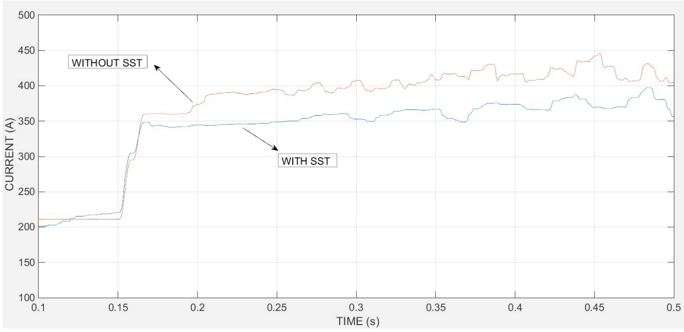

Figure 6. Data center current under increase critical load.

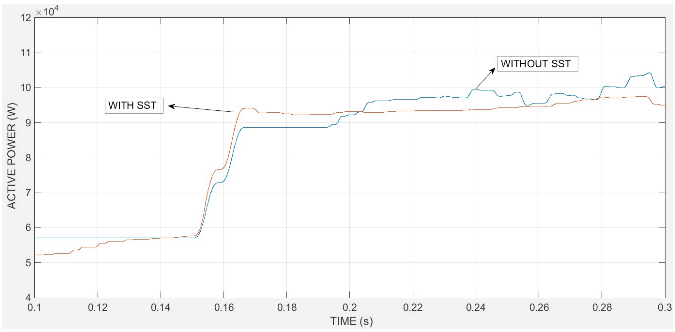

Figure 7. Data center active power when critical load increased.

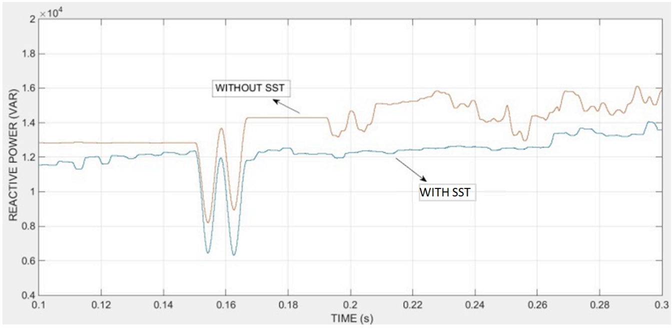

Figure 8. Data center reactive power under the increased critical load

B. Decreasing critical load (underloading)

The simulation scenario starts with normal operation of the data center, power supplied by main utility, and critical load is at its 25% capacity. Then at t=0.15 sec., critical load is decreased to 15% of its capacity to simulate decline in IT load. This causes so-called voltage swell and a drop in current. However, voltage should be come back to the same level of 480V after the transient period.

Similar to previous scenario, SST shows better performance in controlling power parameters. Figure 9 shows that SST successfully returns voltage to the nominal value after the transient period, while typical data center voltage settles to marginally higher level. SST also is capable to smooth current fluctuations as shown in Figure 10. Active and reactive power both effectively dampened by the SST (Figure 11 and Figure 12), demonstrating that SST has better dynamic response.

Thanks to native voltage control of SST, the reactive power curve is smoother than the curve of the typical data center.

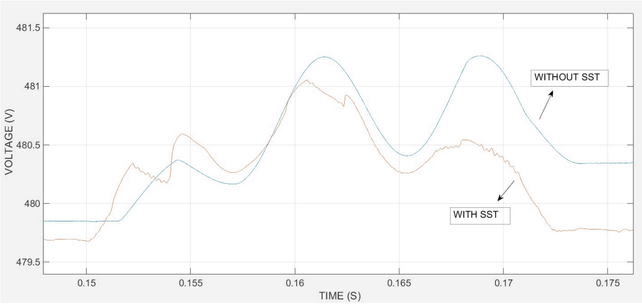

Figure 9. Data center voltage when IT load decreased.

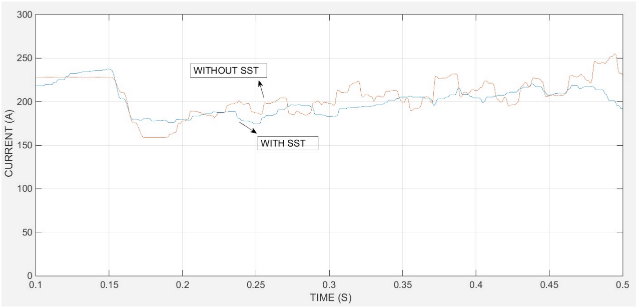

Figure 10. Data center current with IT load decline.

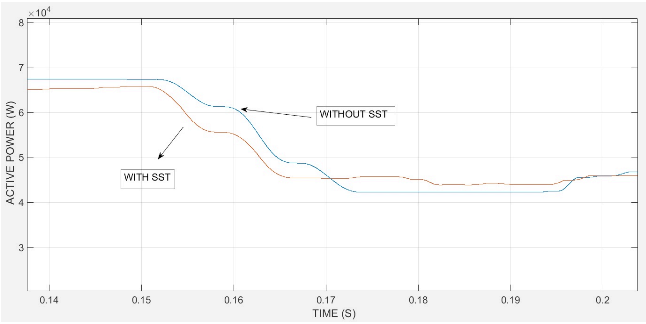

Figure 11. Data center active power when critical load decreased.

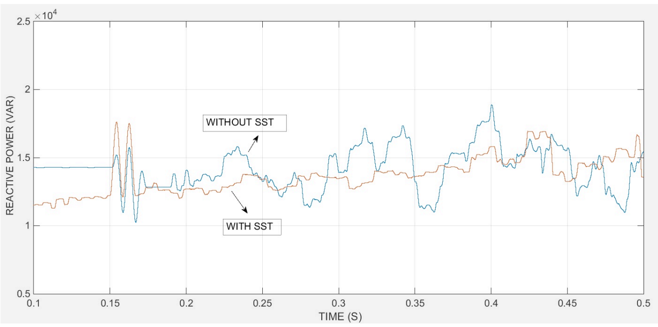

Figure 12. Data center reactive power when critical load decreased.

C. Islanding mode

In this scenario, it is assumed that at 0.15 sec. a fault occurs in the regional network, cutting power to the data center. ATS automatically moves the data center load to the standby generators. Generator is in online standby mode; however, UPS ensures uninterruptible and smooth power supply for critical load. This transient process causes variations in voltage, current and power, affecting equipment such as cooling fan motor.

Figure 13 and Figure 14 show voltage and current of the data center in the transient period. SST maintains smoother curves, thanks to the SST native voltage controller and current limiter. When transitioning to backup generator, the distortion in voltage and current is expected. However, SST maintains power quality in the transitional period and the process of switching to the standby generation has gone almost unnoticeable to the data center load.

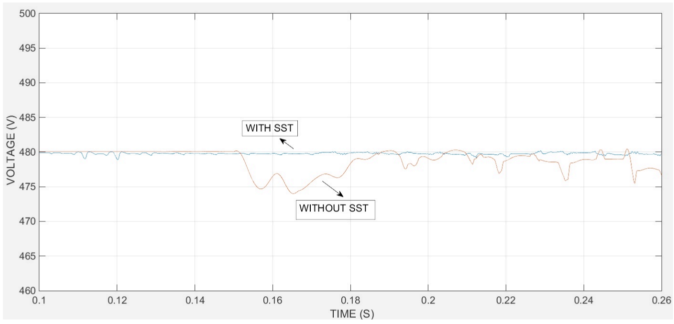

Figure 13. Data center voltage in islanding mode.

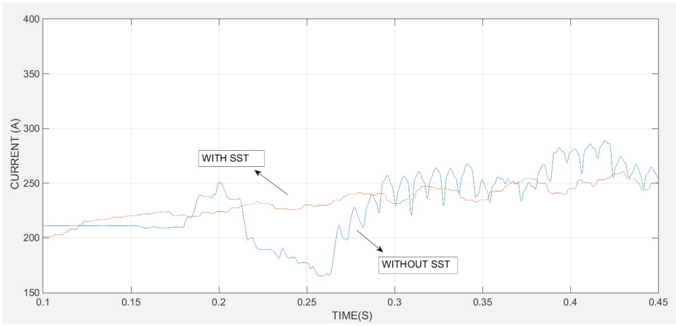

Figure 14. Data center supplied by backup generator: electric current.

Figure 15 and Figure 16 show active and reactive power respectively. Again, SST demonstrates better control of the power characteristics. The difference is obvious: model with SST exhibit flatter curves. This is important for dynamic loads such as motors, pumps and batteries. Stable power ensures system stability, reliability and reduces overall power loss in the infrastructure and equipment.

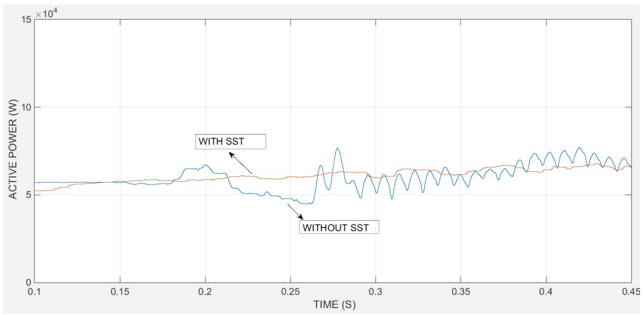

Figure 15. Data center supplied by backup generator: active power.

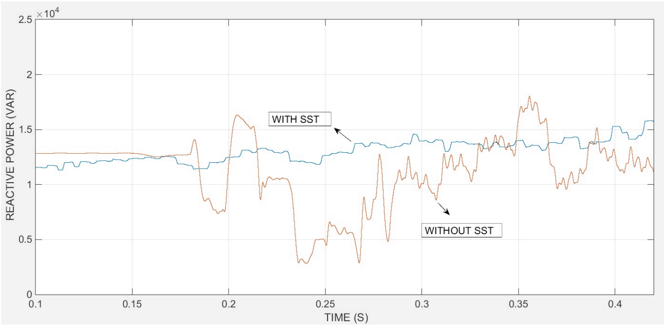

Figure 16. Data center supplied by backup generator: reactive power.

In summary, simulations have shown that integrating SST into the data center power infrastructure has promising results. Since SST contains AC/DC/AC conversion, and the internal control within SST, it by default conditions incoming utility power. It provides data center with better quality power and automatically shields whole infrastructure from the variations in voltage, current and active and reactive power. These fluctuations can result in heating of electrical equipment, e.g. motors and cables, which leads to inefficiency and safety issues. SST, as part of the infrastructure, helps to reduce mutual impact of different equipment of various systems within the data center facility, such as cooling system, UPS, server rooms, backup batteries, generators and etc. Moreover, SST allows simplifying electrical system of a data center, reducing number of equipment required, avoiding power loss and increasing efficiency.

Conclusion

This paper studied the impact of SST in the data center power distribution infrastructure. The challenging task is to develop appropriate data center models and integrate SST making design decisions. Performed simulation has demonstrated that the SST has potential to improve operational efficiency:

- SST conditions incoming utility power (thanks to AC/DC/AC conversion and internal voltage control);
- SST provides data center with better quality power and automatically shields the sensitive loads from the variations in power characteristics;
- SST allows simplifying the electrical system of a data center, avoiding power loss and increasing efficiency.

Immediate future work that follows is to quantify these performance metrics of improved data center design with SST.

The next stage of the project involves developing an optimal data center design with SST and investigating its potential in demand response actions initiated by network operators to keep the balance of supply and demand within the regional networks. This is an important topic relating to stability and reliability of the grid. SST exhibits necessary and promising capabilities of fast dynamic reaction and its ability to control bi-directional flow of energy.

Moreover, SST can facilitate integration of the renewable sources into the power supply of the data centers. Since renewable sources produce DC power; using SST there is no need to convert it to AC to be used in the facility. SST also allows for bi-directional flow of power, and can serve as an energy hub [6][7]. This can facilitate data centre participation in power balancing activities of the grid.

References

[1] J. Koomey. (2011, Aug. 1). Growth in Data Center Electricity *Use: 2005 to 2010* [Online]. Available: http://www.analyticspress.com/datacenters.html

[2] Mark D. Hill "The Data center as a computer. An Introduction to the design of warehouse-scale machines"

[3] T. Furlong, J. Park, (2012), "Open compute project: data center design", *The Green Grid,* URL www.thegreengrid.org

[4] Open Compute Project. *Energy efficiency*. 2011; Available from: http://www.opencompute.org/about/energy-efficiency/

[5] R. Sawyer, "Calculating total power requirements for data centers", APC white paper 3

[6] Xu She; Burgos, R.; Gangyao Wang; Fei Wang; Huang, A.Q., "Review of solid state transformer in the distribution system: From components to field application," *Energy Conversion Congress and Exposition (ECCE), 2012 IEEE* , vol., no., pp.4077,4084, 15-20 Sept. 2012

[7] Tiefu Zhao; Jie Zeng; Bhattacharya, S.; Baran, M.E.; Huang, A.Q., "An average model of solid state transformer for dynamic system simulation," *Power & Energy Society General Meeting, 2009. PES '09. IEEE* , vol., no., pp.1,8, 26-30 July 2009

[8] S. Kieffer, W. Spencer. A. Schmidt, S. Lyszyk, "Planning a data center", 2003

[9] Hewlett-Packard development Company, L.P., Hp Power Advisor. 2015.

[10] Sawyer, R., (2004). "Calculating total power requirements for data centers", white paper 3, in *American Power Conversion (APC)*.

[11] Huang, A.Q.; Crow, M.L.; Heydt, G.T.; Zheng, J.P.; Dale, S.J., "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," Proceedings of the IEEE , vol.99, no.1, pp.133,148, Jan. 2011 doi: 10.1109/JPROC.2010.2081330

[12] Xiaolin Mao; Falcones, S.; Ayyanar, R., "Energy-based control design for a solid state transformer," Power and Energy Society General Meeting, 2010 IEEE , vol., no., pp.1,7, 25-29 July 2010 doi: 10.1109/PES.2010.5590097

[13] Falcones, S.; Xiaolin Mao; Ayyanar, R., "Topology comparison for Solid State Transformer implementation," Power and Energy Society General Meeting, 2010 IEEE , vol., no., pp.1,8, 25-29 July 2010 doi: 10.1109/PES.2010.5590086