Structured Microgrids (SμGs) and Flexible Electronic Large Power Transformers (FeLPTs)

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(Invited)

Abstract **– Structured microgrids (SμGs) and Flexible electronic large power transformers (FeLPTs) are emerging as two essential technologies for renewable energy integration, flexible power transmission, and active control. SμGs provide the integration of renewable energy and storage to balance the energy demand and supply as needed for a given system design. FeLPT's flexibility for processing, control, and re-configurability offers the capability for flexible transmission for effective flow control and enable SμGs connectivity while still keeping multi-scale system level control.**

Early adaptors for combined heat and power have demonstrated significant economic benefits while reducing environmental foot prints. They bring tremendous benefits to utility companies also. With storage and active control capabilities, a 300-percent increase in bulk transmission and distribution lines are possible without having to increase capacity. SμGs and FeLPTs will also enable the utility industry to be better prepared for the emerging large increase in base load demand from electric transportation and data centers. This is a win-win-win situation for the consumer, the utilities (grid operators), and the environment. SμGs and FeLPTs provide value in power substation, energy surety, reliability, resiliency, and security. It is also shown that the initial cost associated with SμG and FeLPTs deployment can be easily offset with reduced operating cost, which in turn reduces the total life-cycle cost by 33% to 67%.

***Index Terms*–Structured microgrids, flexible electronic large power transformers, energy systems, renewable integration, grid modernization, active control, life- cycle cost.**

I. Introduction

RENEWABLE energy is gaining momentum in bulk generation of electricity [1], despite of the fact that traditional gas and oil are still dominate [2]. With about 2/3 of the total global investment going to solar and wind energy, renewables are also projected to surpass coal in less than a decade as the price for wind and solar gains price parity or even lower in price than coal [3]. One of the salient features of the wind and solar PV power is its intermittent nature of energy availability, particularly when it comes to connect these renewables to a power grid. A structured microgrid (SμG) is a natural vehicle to integrate all forms of renewables into an autonomous subsystem or/then system [4].

For grid deployment of renewables, SμGs provide benefits beyond integration. It can provide a whole slew of benefits such as demand response, energy storage as spinning reserve, ancillary support in addition to bulk generation and distribution [5]-[8]. SμGs are also powerful in turning common back-up generator sets from idle to active assets for revenue generation. It can also act as a basic building block for a modern electronic grid, as envisioned in [9], where six basic characteristics of a modern grid are discussed in detail. Despite of their many advantages and because of the required high reliability for electricity, SμGs are still facing certain challenges, particularly in first cost, uncertainty about life cost, lack of adequate availability of system integrators, and regulatory barriers [14]. As a result, utilities are still currently reluctant to fully embracing SμGs [15].

Flexible electronic large power transformers (FeLPTs) are emerging as the key equipment to fully realize the benefits of renewables and SμGs. It is a class of electronic power transformers that focus on renewable integration and flexibility in transmission [16]-[19]. FeLPT is a general term used to describe electronic power transformers at megawatts levels for typical grid and traction applications. Other terms used include Smart Transformers, Power Electronic Transformer, Solid-State Transformers, etc.

This paper attempts to present the case of SμGs and FeLPTs together as twin technologies to enable renewable integration and flexible transmission. Section II reviews the definition of structured microgrids and the local benefits to the owner and global benefits to the next-higher level power sub-grids or grids. Section III summarizes the basic roles and capabilities that storage and active control play in microgrids and in power grids. Section IV discusses the issue of life-cycle cost can be significantly less for a microgrid owner. The first cost associated with a microgrid deployment can be offset by reduction in operational cost. Section V presents a summary of 10 top applications for SμGs, together with one example for the SμGs to triple the transmission capacity by 300% without having to increase the transmission or distribution line capacity, proving hence that SμGs are ultimate grid assets for any utilities to own and operate. Section VI puts forward the state of the art and the challenges for FeLPTs. Finally, we present conclusions and relevant references.

II. Structured Microgrids

Microgrids have emerged as natural vehicles for integration of renewables into a systems or a subsystem with multi-physics. Among the many types of microgrids, structured microgrids (SμGs) are powerful, flexible and easily scalable. The concept of SμGs was first introduced in 2015 [3]. It is recaptured here for easy reference.

Definition: A structured microgrid, dc, ac, or a hybrid of dc and ac, is an integrated autonomous, multi-physics energy

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system (or subsystem) with loads, energy sources, storage devices, energy processing circuits, sensors, active controllers, data buses and data processing, which features the following:

- Balance of energy over the intended operation and design capacity
- Re-configurability for stand-alone or grid-connected operations
- Resiliency with fault tolerance and fault isolation
- Bidirectional power flow
- Scalability and modularity

Local Benefits: There are many benefits that a microgrid brings to its owners locally, including

- Enhanced energy efficiency
- Reduced electricity cost
- Improved power quality
- Greater availability of power (particularly with grid)
- Enhanced energy independence
- Combined utility generation (gas, heat, water, and communication
- Environmental conservation using renewables
- Creation of a natural platform for local generation and integration
- Resiliency with redundancy and recovery
- Building blocks for the next higher-level grid(s)

Global Benefits: Besides local benefits, microgrids bring benefits globally to the grid and surrounding communities by

- Enhancing distributed generation with a high percentage of renewables
- Enhancing distributed storage
- Accommodating emerging demand from electric vehicles
- Allowing smart metering to do transactive (dynamic) pricing
- Enabling local energy management without burdening the grid bandwidth for communication
- Preprocessing data locally to reduce the required grid bandwidth for command and telemetry (SCADA)
- Providing predictive local control to enhance grid stability
- Using bidirectional flow to enhance energy availability to grid
- Providing a balance between the distribution grid and microgrids
- Using their ability to island and for black start

DC microgrids are particularly advantageous for practice due to their many benefits, including higher efficiency, more robust system operation, no impedance matching issues, no synchronization, simple waveforms, and a large body of knowledge in power electronics and systems being directly leveraged [4]-[6].

III. Storage and Active Control

The three salient features that separate a structured microgrid (SμG) from a traditional microgrid are: 1) storage devices, 2) active controllers, and 3) autonomous operation [4].

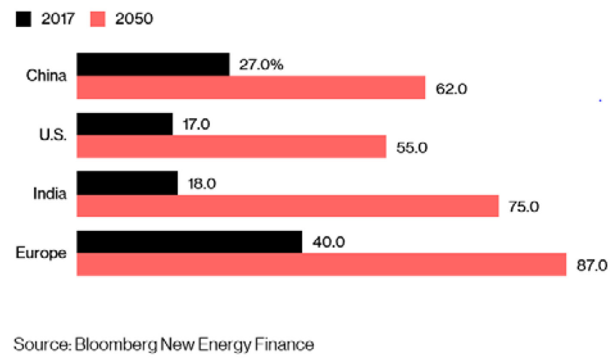

Fig. 1: Key economies around the world are projected to be running at least 55% renewable energy by 2050

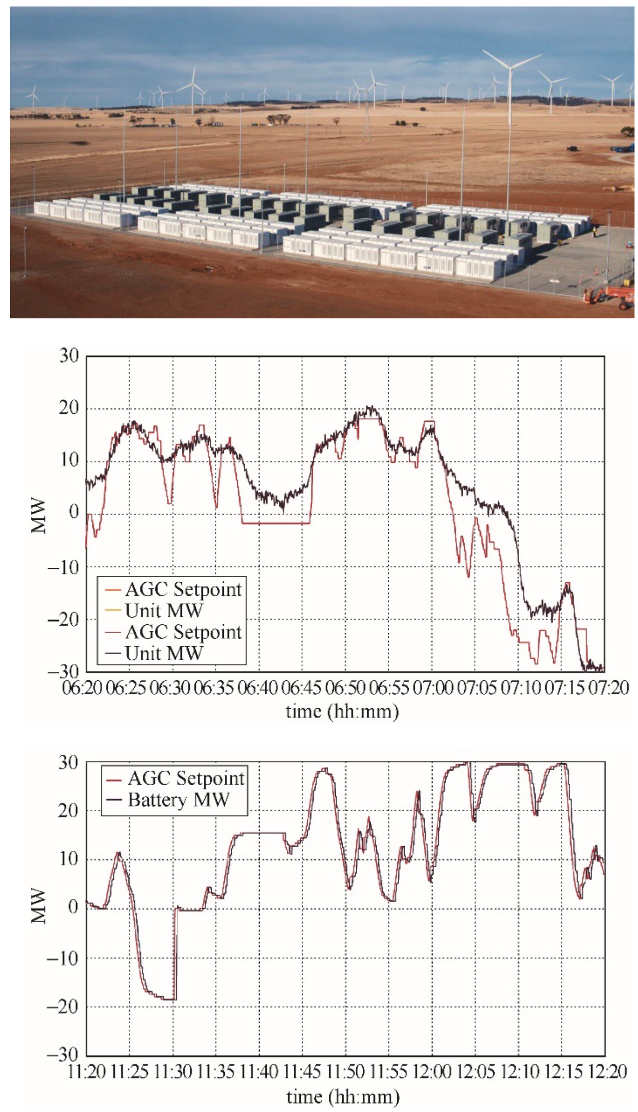

Fig. 2: The Hornsdale battery farm in Southern Australia (top): Accuracy and response time are much superior to those provided by large–steam-turbine-based spinning reserve (bottom), proving that batteries (in a SμG) provide ultimate inertia [12].

A. Storage and Energy Balance

Among many forms of storage, batteries are the most efficient and versatile. They can be fast charged and discharged. Batteries are essential for SμGs since they provide the ability to stow energy when it is abundantly available with

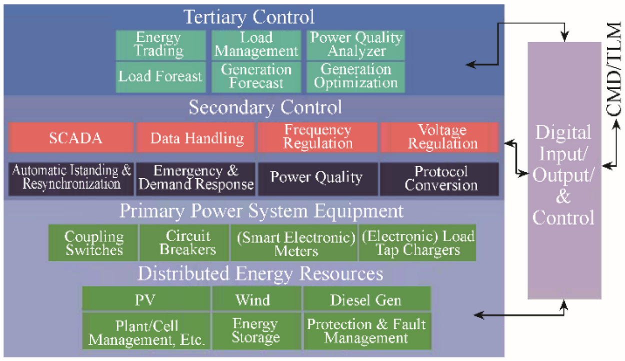

Fig. 3: Typical structure of an active controller for SμGs with five (5) levels of control and coordination [19], [20]

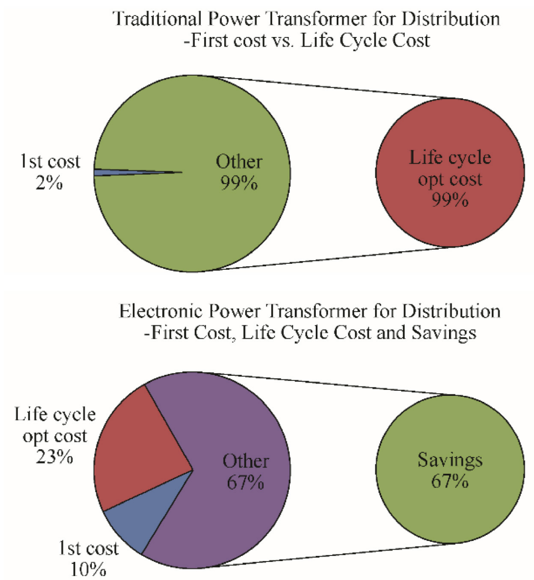

Fig. 4: The first cost of a traditional (electromechanical) utility transformer only occupies 1% of its life-cycle cost. The first cost of an electronic utility transformer can occupy up to 10% of the total life-cycle cost, with the total life-cycle cost 33% with improved performance, a cost reduction of 67% for the total ownership [18]

surplus and to release energy when it is least available with deficit. This feature enables an energy system to achieve its energy balance in a useful time frame, even with a time shifts [9]. It can also store and dispatch energy with electronic means in a timely fashion [12]. Battery is the last missing piece for SμGs to impact field deployments to provide full benefits for grid operations. Grid-scale deployments of batteries are quickly emerging such as those with Southern California Edison's 20MW Li- ion battery deployment with 80MWh to power 20,000 customers for 3 hours (January, 2017), San Diego Gas & Electricity's 30MW Li-ion battery deployment with 120MWh capable of powering 20,000 customers for 4 hours (February 24, 2017), and the world's large installation in Hornsdale, South Australian with 100MW and 129MWh capacity (November 28, 2017).

A recent report by the Australian Energy Market Operators for the Hornsdale facility presented for the first time field measured response for their installed grid-scale batteries "farm" providing frequency control ancillary services (FCAS) in Southern Australia [12]. Refer to Fig. 2. The bottom left plot of the figure shows the response to the FCAS command in the time domain. It is seen that the system responded sluggishly. Sometimes, it could not even respond (flat portions). The bottom right plots of the figure shows the FCAS responses when the installed batteries are used as the spinning reserve.

It is seen that the response followed the commands almost instantaneously. The command (Black) and response (Red) curves are almost indistinguishable. The FCAS services that the battery farm provided are "rapid, accurate and valuable." Compared to a typical synchronous generator's mechanical inertia, batteries provide "ultimate inertia" for super-fast response for the grid operators.

B. *Active Control*

Active control is yet another important feature of the SμGs. (Note: The original power station by Edison on the Pearl Street in Lower Manhattan, New York, was not a SμG, since it did not have storage nor active control.) A typical structure for an active controller is presented in Fig. 3. The controller extends the traditional 3-level hierarchical control for a synchronous generator set by inserting a lower-level control layer for the renewable sources [13], [14].

Additional digital controller loop can be used to provide more flexibility and functionality for autonomous digital control, input/output command and telemetry, data processing, mode control, and state-of-health monitoring and protection [15], [16]. Therefore an active controller can have up to five (5) layers of control. Since the different hierarchical layers work in multiple different time scales, care must be taken to coordination of loop bandwidth, especially for large-signal dynamics. To that effect, an energy-balance-based control is essentially important, as illustrated in [17].

C. *Autonomous Operation*

Autonomous operation for any SμG is crucially important, since it enables a structured microgrid to stand alone with full functionality for steady state, during transients, or for fault survival and recovery [15], [16].

Autonomy also simplifies its interface with adjacent sub-grids or microgrids. It reduces the required communication bandwidth with a central control office such as an independent system operator (ISO) or a regional distribution system operator (DSO) through SCADA [20].

IV. Life-Cycle Cost

SμGs development and deployment go beyond engineering. It requires good understanding of technical, financial, and regulatory issues. For instance, the issue of life-cycle cost is important to consider at the planning phase for a SμG deployment. It is important to point out that the usually high first cost for SμGs can be offset by its higher performance in energy efficiency that brings cost savings over its life cycle.

Fig. 4 presents an example for the case with a utility power transformer. The left graph shows that the first cost of a traditional (electromechanical) utility transformer ($3,177 market price) only occupies 1% of its life-cycle cost of

$287,000, assuming a competitive rate of $0.12/kWh. Assume its electronic counterpart costs 10 times more for $31,765. With efficiency improvement of 7.5%, the total life cost for same operational life of 25 years is reduced to $73,913. This is a reduction of 67% in total life-cycle cost for total ownership; despite of the fact the first cost is 10 times more expensive [18].

The challenge for deployment of grid-scale electronic power transformers lies in that the asset owner (user and consumer) is typically not in the loop for the initial planning and hence the benefits are not factored in when the trade decision is made. The trade for the SμG is a bit more complicated, but the conclusion is similar, since a grid-scale electronic power transformer is a key equipment for any structured microgrid [7], [8].

V. Structured Microgrid Applications

Applications of structured microgrids are numerous – from simple combined heat and power (CHP) to complicated basic autonomous functional building block for a larger grid or sub-grid. A first summary of typical applications for SμGs were presented in [20]. We will discuss some of the key applications here in more detail.

SμGs can be classified into different categories by grid power level or size, such as mini-grids, microgrids, nano-grids, etc. (Size is actually not important.), by ownership, such as building microgrids, community microgrids, campus microgrids, etc., or by functionality such as DC or AC microgrids, and by applications. In the following discussion, we will use application classification to allow more concise discussion on salient features [20].

A. Combined Heat and Power

CHP is an early adaptor for microgrid technology. CHP provides reliable base load power, weather proof gas supply, and heat capture for hot water, chilled water and steam for heating. A campus-wide SμG was deployed by UCSD [21]. It features self-generation of 85% electricity, 95% heat and cooling, 30MW CHP plant with heat recovery, storage, solar power with weather forecast, backup generators, etc.

It is reported that the UCSD campus microgrid saves the university greater than $10M in electricity cost, together with a 40% CO_2 reduction annually [21]. If the initial first coat for the deployment is $100M, then the cost will be recovered in only 10 years. For a typical life time of 25 years for power equipment, there will be 15 years left for the asset to generate net cost savings for the owner.

B. Data Centers

With the increase of the amount of data that is becoming available for consumers and service providers, the required power has increased exponentially. It is projected to reach 4% of the total CO_2 emission [22]. Equally important is its related thermal removal requirement. A typical ratio for power and heat removal is 55%/45%. A useful metric is the reductions in CO_2 emission and electricity consumption can be achieved through improved value of the power usage effectiveness (PUE).

Improvement of PUE can be accomplished through various energy efficiency measures such as locations in cold places, for instance. But recent trend is to localize energy demand and management to local areas through energy efficiency, computational power optimization, and integration of locally available renewables such as solar and wind. To this end, configuration of power infrastructure for data centers into structured microgrids has the largest potential [23].

C. Demand Response

Demand response (DR) has recently attracted a large amount of attention from utilities. The left plot of Fig. 5 shows a typical case for demand response in time domain. It is clearly seen that demand response is more effective than power curtailments. The Federal Energy Regulatory Commission projects that DR will significantly increase. The right plot of Fig. 5 shows another aspect of DR– active pricing. Because of its nature of being an actively controlled, a SμG can provide the infrastructure for active demand response [24] with clear economic benefits.

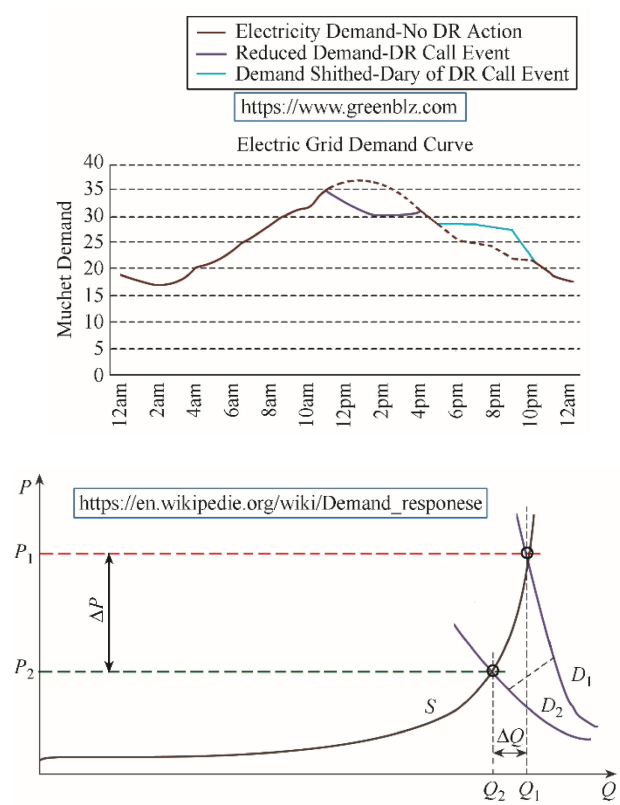

Fig. 5. SμGs provide flexible, ultimate demand response

D. Ancillary Support

SμGs are versatile in providing grid support capabilities as summarized in Fig. 6. SμGs can provide just about any functionalities that grid operators would like to have, including, but not limited to, efficiency enhancement, resiliency, reliability and availability; natural integration of renewables; local storage for energy balance; ultimate demand response, including peak shaving; ultimate spinning reserve; ultimate linearizer for reactive load and renewables; automation for substations; autonomous protection and fault management; autonomous flow control/communication for transactive energy; and ancillary support (frequency regulation, Volt/Var control, power factor correction and Harmonics) [20].

It covers the entire range of supply chain for electricity supply – from bulk generation to transmission to distribution (T&D) to grid edge to consumers [20]. Among the many functions, ancillary support is a critical service for grid operation [25]. Fig. 7 shows the measured results for frequency regulation obtained from a university-campus structured microgrid [26].

E. Substation Automation and Electronictization

Another large area for SµGs applications is to configure a substation as a SµG, where renewable energy, storage and active control can be seamlessly integrated to enhance the reliability, resiliency and stability locally [27]-[30].

With the injection of local energy into the substation, the voltage profile for the T&D can be enhanced [28]. The ability

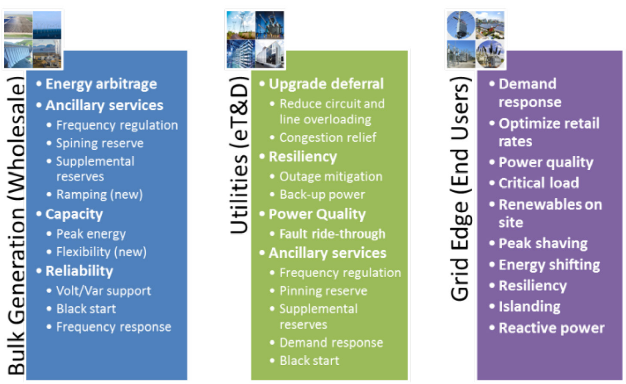

Fig. 6. SµGs provide versatile grid support capabilities [20]

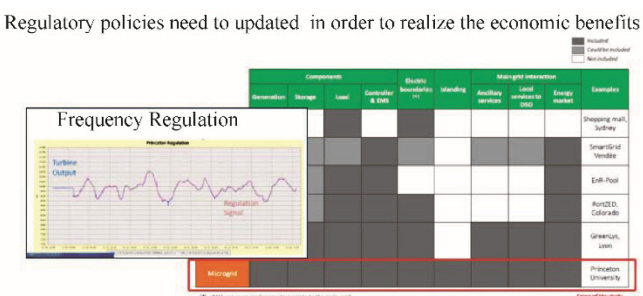

Fig. 7. Structured microgrids can naturally provide ancillary support for grid stabilization.

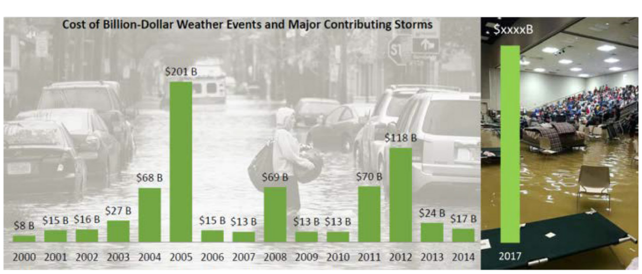

Fig. 8. Cost of billion-dollar weather event are staggering [32].

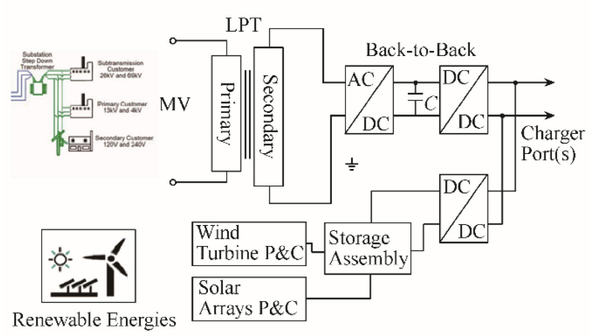

Fig. 9: Super-fast charging infrastructure [31]

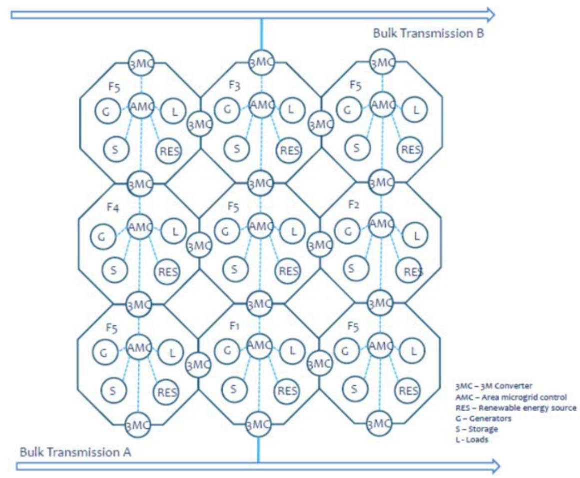

Fig. 10. A fractal structure for meshed power network with SµGs as the building blocks [9]

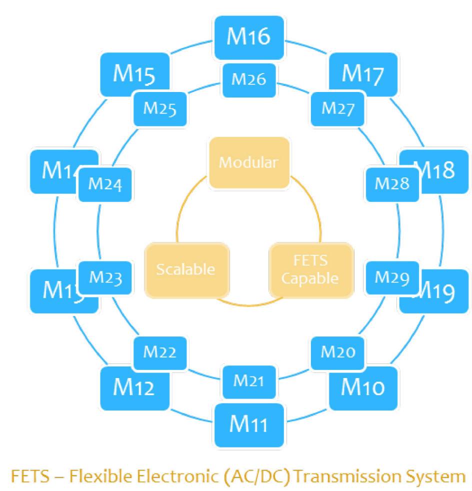

Fig. 11. Flexible electronic power transformer is a key element for SµGs and grid modernization [7], [8].

for Volt/Var control can enhance the stability of the local grid. Furthermore, with independent energy from local renewable integration and with equipment from the family of All-Things-Grid-Connected [4], many power flow control techniques, such as unified power flow controller (UPFC), can be applied to a substation, which in turn will strengthen the grid locally [29], [30].

F. Ultra-Fast Battery Charging Station

Challenges for ultra-fast battery charging power stations include: accommodation of up to four (4) levels of charging requirements, efficient battery operation and maintenance, adiabatic and flexible power conversion, high power level at burst rate, integration of renewables, low lifecycle ownership cost, grid support, reliability, and long operational life [31].

Ultra-fast charging demands power level up to 300kW each. For a multi-station charging facility, this can easily go into megawatts range. Direct connection to the grid by this amount of power will impact power quality and even grid integrity, particularly where the grid is weak. A superior approach is to configure a charging station as a SμG to integrate renewables with storage and to provide grid support services to make business case feasible [31]. Fig. 9 is an illustration of such a SμG configured as an ultra-fast charging station.

G. Stand-Alone and Remote Energy Access

Stand-alone and remote microgrids include spacecraft, aircraft, or ship applications, or public transportation, or applications in a remote geographical area where large-scale deployment of power delivery infrastructure is economically infeasible.

The energy access can be ensured through a remote, stand-alone SμG (No requirement for grid connection). The SμG can provide the require energy by integrating local renewable energy with solar, wind, or geothermal [7], [8].

H. Critical Infrastructure and Resiliency

Critical infrastructures include hospitals, airports, transportation command centers, grid operational control centers, emergency response centers, law-enforcement institutions, etc. The electricity availability for a prescribed extended time of operation after the emergency is an absolute requirement. The common practice is to use a back-up generator set with adequate capacity to fulfill the requirement [32].

Recent increased awareness of cyber security issue that can potentially cripple a power grid had led to the requirement for a power grid to have built-in protection against natural or man-made disasters. While cyber security is usually treated as a software/firmware issue, a SμG can provide the ultimate protection, where hardware based protections can be implemented to bypass the digital control driven by software/firmware and maintain or restore the essential functions for the system [15].

I. Basic Building Blocks for Electronic Grids

SμGs can serve as the basic building blocks for the future electronic grid (eGrid). It can either support a traditional meshed power network or as a redial power network [9]. Figure 10 shows a fractal meshed structure. A modular, multi-level, and multi-time scale converter (3M) can be the basic elements for interconnects and power flow control as required [29].

J. Physical Transactive Energy

With the alignment of regulatory policies more towards transactive energy, the full potential of structured microgrids can be further realized to allow physically determining how energy transactions are directly performed from consumers to consumers, without having to go through aggregation process first and then distribution, all through an ISO or DSO. This unprecedented capability is bring about by the powerfulness of SμGs because of its energy balance and active control capabilities [19], [20] and with its ability to control phase angle independently.

A structured microgrid integrates and linearizes renewable energies naturally to the power grid. The traditional grid operator such as ISO can play the same role in bulk generation and transmission.

For instance, with peak shaving (demand response with storage), the existing transmission lines can carry twice (2x) as much power. With power factor correction (linearization), the existing transmission lines can carry 1/0.68=1.47 times more power. So with the existing lines, grid modernization will triple the transmission and distribution capacity, a win-win-win for consumers, grid operators, and the environment. With SμGs capability for renewable integration and active control, the utility company can triple their transmission and distribution capacity without having to increase transmission line capacity [20].

VI. Flexible Electronic Large Power Transformers

Structured microgrids (SμGs) and flexible electronic large power transformers (FeLPTs) are emerging as two essential technologies for renewable energy integration and active control for flexible power transmission. The early concept of FeLPTs was introduced by the author [7]-[9]. The conceptual illustration is captured in Figure 11. A FeLPT features 3M as its characteristics: Modular in its composition, Multi-level within its power processing, and Multi-time-scale in its control [6]-[9].

A FeLPTs flexibility in processing, control, and re-configurability offers the capability for flexible ac transmission with effective power flow control. It can also integrate SμGs' connectivity while still keeping multi-scale system level control [29], [30]. SμGs provides the integration of renewable energy, active control, and storage capacity to balance the energy demand and supply automatically.

Challenges in SμGs integration include accurate forecast for renewable availability, cost-effective design, and efficient control (Grid forming or following). Challenges in FeLPTs include efficiency, reliability, size and cost parity as discussed below.

A. Challenges for FeLPTs designs

Challenges for FeLPTs designs are in three general areas. The first one is to achieve ultra-high power efficiency with multiple power processing stages as required for power station applications to reduce operational cost (electricity bill). The second challenge is to obtain high reliability over the entire design life, say, for more than 25 years. The third challenge is to achieve control flexibility to support grid operations while ensure local power supply with voltage and frequency control.

Take a typical distribution power substation as one example. Figure 12 is a typical FeLPT architecture for power substation applications [33]. There are three major sub-conversions: A front-end conversion circuit to interface with the grid, an intermediate conversion circuit for isolation, and voltage scaling (A dual active bridge for this case), and low-voltage conversion to interface with users.

As reported by the authors, the various losses are presented in Figure 13. The first sub-conversion is typically the rectification to obtain a dc voltage (or vice versa). This stage is typically highly efficient as shown in the Figure 14 to be 99.46%. The second sub-conversion is to provide isolation and voltage scaling at relatively high switching frequency. The efficiency is projected to at 98.33% for a well-designed circuit. The galvanic isolation transformer usually take close to a 1% of power loss, which is the obstacle for the intermediate conversion to be adiabatic (>98.5% efficient). The third sub-conversion is on the relatively low voltage side for the user interface. The achievable efficiency is at 96.5% only, the lowest among the three. The underlining reason is the need to process high power with large amount of current and relatively low voltage levels.

Figure 14 presents details on opportunities and challenges to improving the design. Figure 14 (1) is the baseline design loss breakdown. Fig. 14 (2) shows that the switching loss, for instance, can be reduced by 50% by changing the circuit topology from Neutral Point Clamped (NPC) to Neutral Point Paralleled (NPP).

Fig. 14 (3) shows the challenges we are facing in achieving the improvements required to obtain adiabatic power conversion for the intermediate sub-conversion. To achieve 99.49%, we need change NPC to NPP for 1/2 reduction of switching loss, use better FETs for 1/2 to ¾ reduction of conduction loss, and better techniques for ½ reduction of total transformer loss. That is, we need 0.5% loss transformers. This represents a significant challenge. Recent advancement in techniques towards 99% efficiency and 99% duty ratio [34] can potentially help make progress towards that goal.

Fig. 14 (4) shows the numerical numbers that we need to achieve 99.49% for the low-voltage conversion portion with reduction of ½ for both the switching and conduction loss. Better switching devices [19] and better circuit topologies can help achieve the goal [34].

B. *Flexibility and Versatility*

A FeLPT is a flexible power device. Its terminal behavior is reconfigurable to be resistive, capacitive, inductive or any combination, commendable from the central control or dispatcher. Figure 15 is an illustrative diagram for a multi-converter configuration as presented in [35]. This generalized

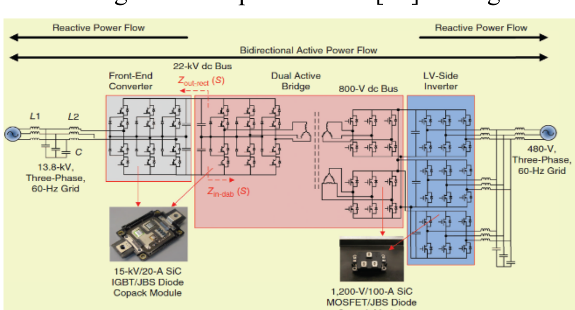

Fig. 12. A typical FeLPT architecture [33].

TABLE VIII
TIPS OVERALL LOSS DISTRIBUTION

Loss Component	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
Switching Loss (W)	440	688.2	297	1425.2
Conduction Loss (W)	102	595.1	738	1435.1
HF Transformer Loss (W)		390		390
Total Loss (W)	542	1673.3	1035	3250.3
Efficiency (η%)	99.46	98.33	98.97	96.75

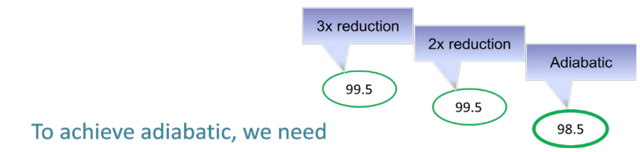

Fig. 13. Summary of challenges that a FeLPT design faces [19].

	Loss Component (W)	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
1	Loss Component (W)	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
	Switching Loss	440	688.2	297	1425.2
	Conductin Loss	102	595.1	738	1435.1
	HF Transformer		390		390
	Total Loss	542	1673.3	1035	3250.3
	Efficiency (%)	99.46	98.35	98.98	96.85
2	Loss Component (W)	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
	Switching Loss	220	688.2	297	1205.2
	Conductin Loss	102	595.1	738	1435.1
	HF Transformer		390		390
	Total Loss	322	1673.3	1035	3030.3
	Efficiency (%)	99.68	98.35	98.98	97.06
3	Loss Component (W)	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
	Switching Loss	220	172.1	297	689.05
	Conductin Loss	102	148.8	738	988.775
	HF Transformer		195.0		195
	Total Loss	322	515.8	1035	1872.825
	Efficiency (%)	99.68	99.49	98.98	98.16
4	Loss Component (W)	FEC (UPF)	DAB	Low Voltage Side (UPF)	Total Loss
	Switching Loss	220	172.1	148.5	540.55
	Conductin Loss	102	148.8	369.0	619.775
	HF Transformer		195.0		195
	Total Loss	322	515.83	517.5	1355.325
	Efficiency (%)	99.68	99.49	99.49	98.66

Fig. 14. Numerical examples to highlights the challenges [19].

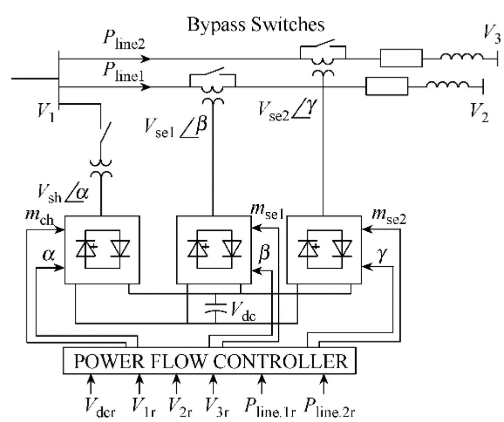

Fig. 15. A FeLPT can be derived from a multiple converter system [35]*Challenges for FeLPTs designs*

unified power flow controller (GUPFC) uses three independently controlled converters to realize its general unified flow control. It can be shown that the GUPEC can be implemented with a coupled three-winding magnetic structure to form a three-phase power transformer. Hence a FeLPT can simultaneously serve as a power transformer and as a flexible transmission device. This unprecedented functionality brings significant benefits as outlined below.

C. *Benefits of FeLPTs*

We note that renewable energy integration provides the required freedoms of control with 3 angles and 3 amplitudes as the control variable. Hence the FeLPTs can be a true FACTs device. Its combined capability for power transfer and flow control provides value added for electronic large power transformers to offset its potentially high cost with unprecedented capability to system operators, grid assets owners (utilities) and consumers.

As the technology progress, successful integration of solar and battery energy systems has proven to be technically effective and economically beneficial. Australia Handsdale Solar Farm has reduced the operator cost by tens of millions of dollars [12]. Recent advancement has even demonstrated that solar and storage based peakers can cost less than gas based ones as recently reported in [36]. Large utilities are now building more solar and battery based peakers than gas peakers as spinning reserve.

A FeLPT can also behave as phase angle regulator to enable person-to-person (P2P) trans-active energy by active control as first shown in [7].

VII. CONCLUSION

Structured Microgrids (SμGs) are natural vehicles for renewable energy integration into the power grid. Because of their benefits and their versatility, they are the ultimate assets for utilities and independent system operators.

Early adaptors of SμGs for combined heat and power (CHP) have shown large cost savings with reducing CO_2 footprints.

SμGs enable the utility industry to be better prepared for the emerging large increase in base load demand from electric vehicles and data centers. This is a win-win-win situation for the consumer, the utilities (Independent system operators), and the environment.

SμGs are also powerful in turning back-up generator sets from idle to active assets for revenue generation. They are valuable in power substation automation and in energy surety, reliability, resiliency, and security.

The first cost associated with a SμG deployment can be offset with reduced operating cost, which in turn reduces the total life-cycle cost by 33% to 67%, pending on market rates for electricity.

It is shown that through SμGs' storage, active control and autonomy capabilities, a 300-percent increase in bulk transmission and distribution lines are possible without having to increase capacity.

SμGs will also be extremely useful as a basic building block for future electronic grids and as an enabler for physical transactive energy when integrated with a FeLPT.

Flexible electronic large power transformers (FeLPTs) are ultra-efficient and ultra flexible electronics devices that integrate SμGs to form renewable-energy-based power substations. Key features are modular, multilevel and multi-timescale.

A FeLPT can provide the capabilities that typically required by two traditional devices (power transformer and FACT device) within one subsystem. This unprecedented capability will bring them into coast parity. It will also bring revolutionary capability to enable the power grid's active control with benefits for system operators, grid assets owners (utilities) and consumers.

Challenges for FeLPTs design and deployment lie in obtaining ultra-efficient power conversion with near adiabatic thermal capability and achieving 0.5%-loss electronic power transformer design. Recent advancement in 99% efficiency and 99% duty ratio [34] can potentially provide the needed breakthrough in achieving the goals.

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