Solid State Transformer (SST)

Concepts, Modeling, Applications, Advantages & Challenges

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Power Electronics for Grid Connected Renewable Energy System

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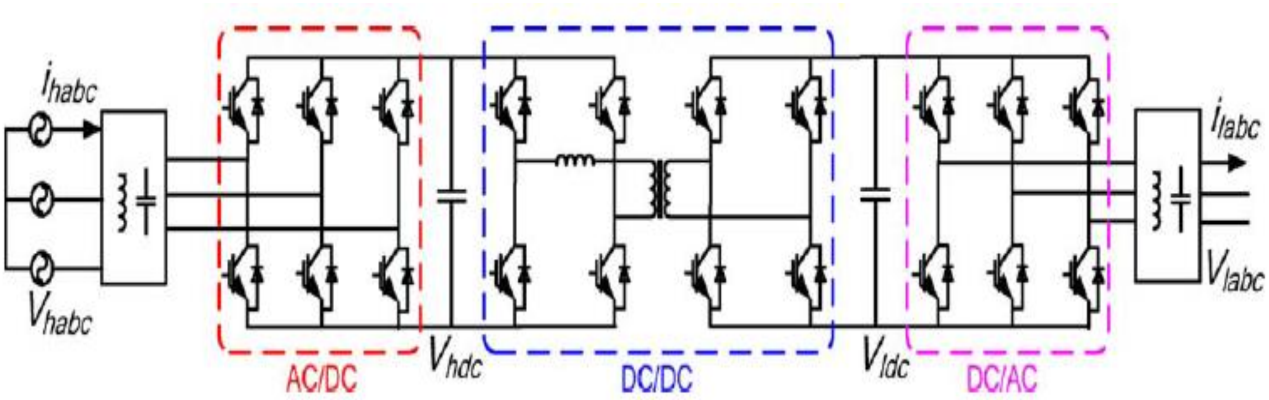
Contents:

1. Introduction

- What is Solid State Transformer (SST)?
- Necessity of SST: Disadvantage of Conventional Transformer.
- Advantages of SST over Conventional Distribution Transformer.
- Development of SST Concepts.

What is Solid State Transformer?

- Solid State Transformer (SST) is an element/component consisted of multi stage power electronics converters isolated with high frequency transformer, proposed in National Science Foundation (NSF) Generation-III Engineering Research Centre (ERC) "Future Electric Energy Delivery & Management (FREEDM) Systems" which was established in 2008 and the proposal of SST was regarded as one of the 10 most emerging technologies by Massachusetts Institute of Technology (MIT) Technology review in 2010.



Disadvantages of Classical Distribution Transformer

- Bulky size and heavy weight
- Transformer oil can be harmful when exposed to the environment
- Core saturation produces harmonics, which results in large inrush currents.
- Unwanted characteristics on the input side, such as voltage dips, are represented in output waveform.
- Harmonics in the output current has an influence on the input. Depending on the transformer connection, the harmonics can propagate to the network or lead to an increase of primary winding losses.
- Relative high losses at their average operation load. Transformers are usually designed with their maximum efficiency at near to full load, while transformers in a distribution environment have an average operation load of 30%.
- All LFTs suffer from non-perfect voltage regulation. The voltage regulation capability of a transformer is inversely proportional to its rating. At distribution level, the transformers are generally small and voltage regulation is not very good.

Advantages of SST over Conv. Distribution Transformer

- Voltage sag compensation
- Outage compensation.
- Instantaneous voltage regulation.
- Fault isolation.
- Power factor correction (and reactive power compensation).
- Harmonic isolation.
- DC output.
- Metering or advanced distribution automation.
- Environmental benefit.

Development of SST Concepts

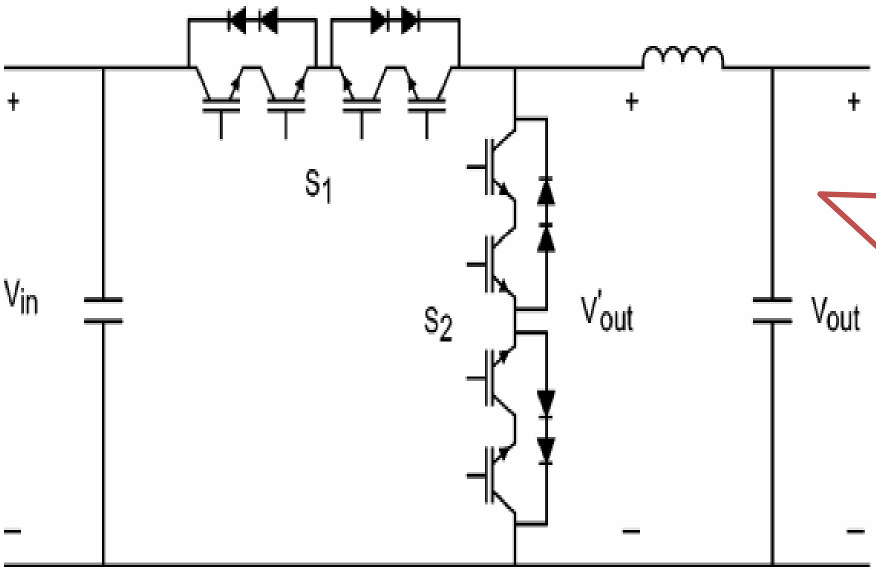
- The idea of a "solid-state transformer" has been discussed since 1970. The initial purpose of solid-state transformers is to convert AC to AC for step-up or step-down with a function the same as that of a conventional transformer.
- In 1970, W. McMurray form G.E. first introduced a high frequency link AC/AC converter, which became the basis for the solid state transformer based on direct AC/AC converter

Cont…

- In 1980, Navy researchers proposed a power-electronic transformer that consisted of an AC/AC buck converter to reduce the input voltage to a lower one.
- This was followed in 1995 by a similar Electrical Power Research Institute (EPRI) sponsored effort.

Achievement

First working prototype



AC/AC Buck Converter

Limitations

- Low Voltage & Power Level
- The use of series tied devices
- Lack of magnetic isolation
- Inability to correct load power factor
- Inability to prevent load harmonics from propagating into the primary-voltage system

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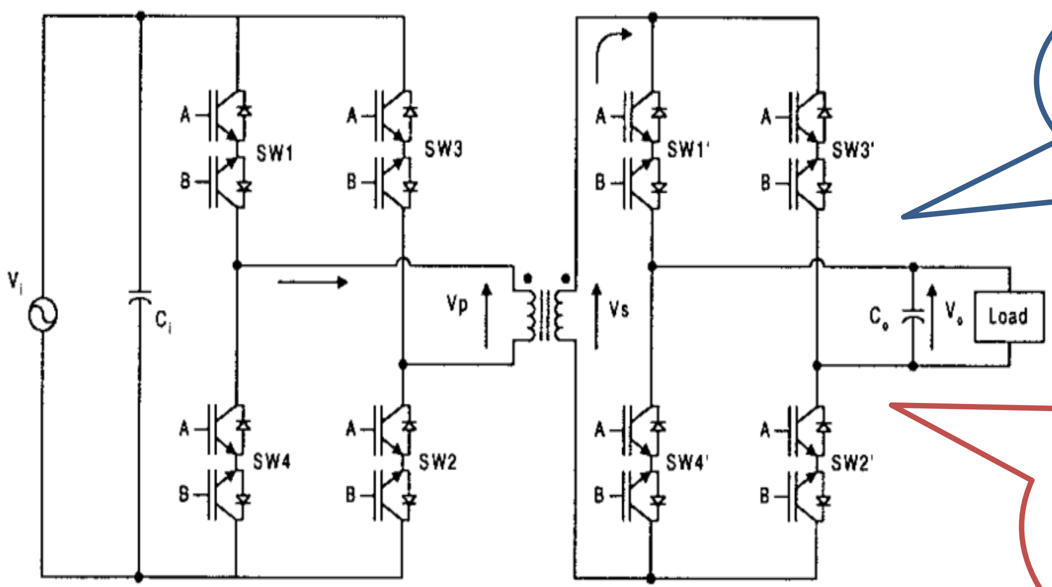
- In 1996, Koosuke Harada proposed a new “intelligent transformer”, which significantly reduce the size of transformers by performing high frequency link.
  - Various functions, such as constant voltage and constant power are realized by phase control.
  - A 200V 3kVA unit operating at 15 kHz was implemented based on this concept.
- **Disadvantage:**
  - The overall efficiency was reported to be about 80%.

Cont…

- A high-power AC/AC conversion has been proposed by Moonshik Kang and Enjeti from Texas A&M University.
- For that topology, the incoming AC waveform is modulated by a power-electronic converter to a high-frequency square wave and passed through a small high-frequency transformer.



High Frequency AC link Converter

Advantages

Reducing the transformer size, weight and the stress factor.

Disadvantages

Does not provide any benefits in terms of control or power factor improvement.

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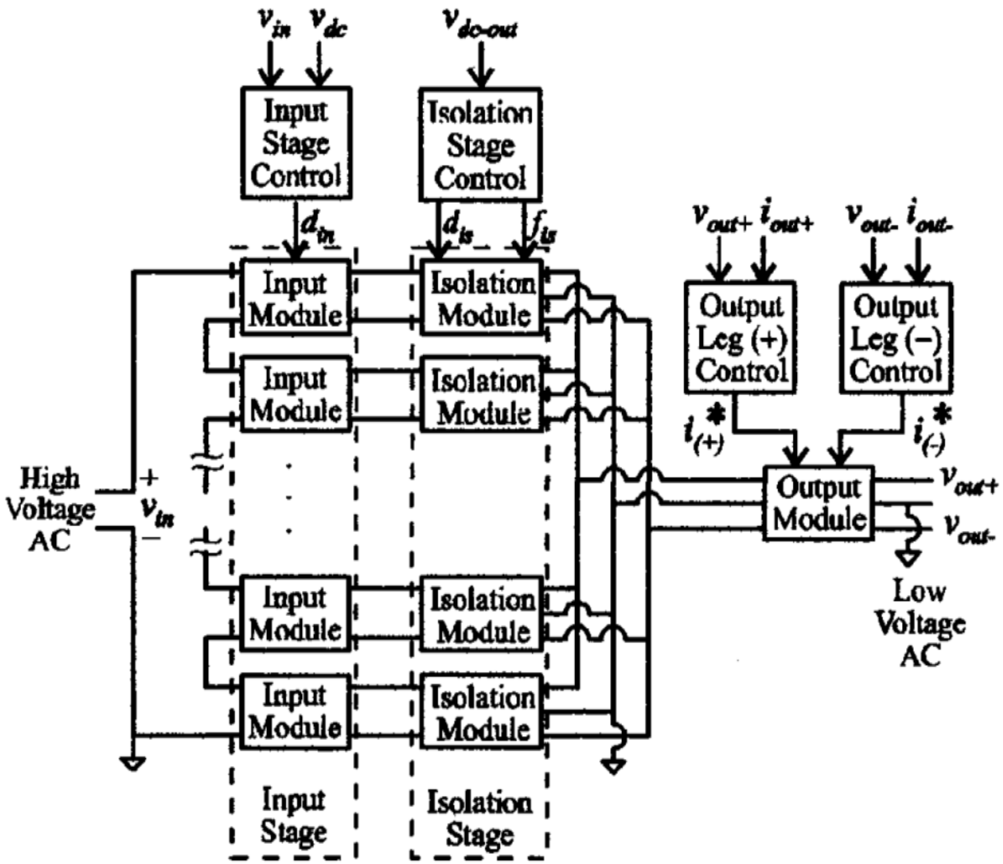
- In 1999, a new structure of SST was introduced by Sudhoff .
- This topology contains three cascaded converters which are power factor controller, isolated DC/DC converter and voltage source inverter.



Advantages

- Achieved size and weight reduction replacing 60 Hz transformer by high frequency transformer and solid state devices.
- Converters are used for programming input current waveform, electrical isolation and output voltage regulation.
- The series to parallel connection of converters has been used to operate properly at medium voltage levels.

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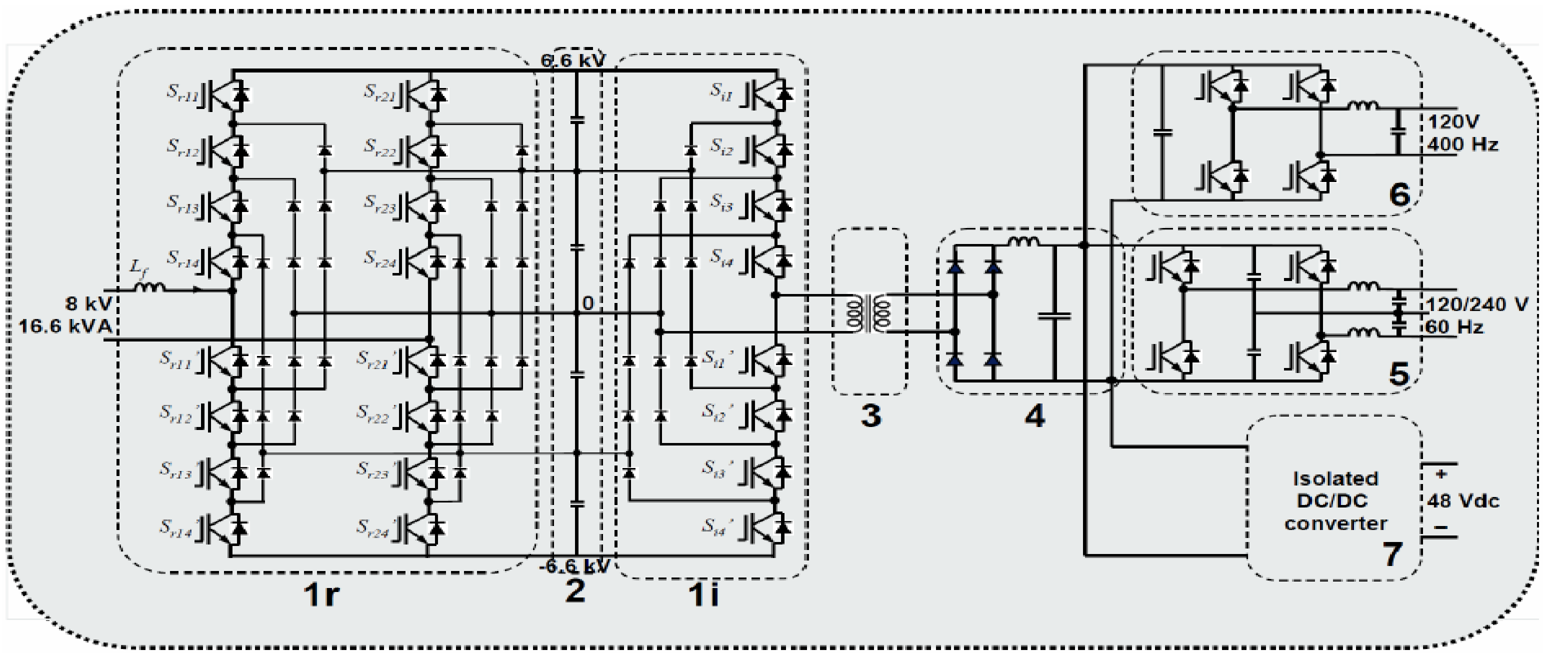
- Since 2002, Electrical Power Research Institute (EPRI) has been researching the Intelligent Universal Transformer (IUT).



- **Advantages:** An intelligent and controllable system can provide multiple transformer functions, such as voltage transformation, voltage regulation, non-standard customer voltages (DC or 400 Hz AC), voltage sag correction, power factor control, and distribution system status monitoring to facilitate automation.

Cont…

- A cycloconverter based SST for low voltage and low power application patented by EATON in 2008.
- Van der Merwe proposed an architecture using a multilevel AC/DC converter and a DC/DC converter with passive rectifiers. This topology was developed for unidirectional power flow in 2009.
- Researchers at ETH Zurich are working on a MATRIX converter with the code name MAGACube.
- The FREEDM project is investigating a SST based on a single phase system with modularity in mind from 2010 onwards.

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	UNIFLEX	*EPRI*	*GE*	*ABB*
Power rating	300 KVA	45 KVA	1MVA	1.2MVA
Phase number	Three	Single	Single	Single
Voltage rating	3.3 KV	2.4 KV	13.8 KV	15 KV
Transformer frequency	2 KHz	20 KHz	20KHz	1.8KHz
Eliminates oil	No	Yes	Yes	Yes
Var compensation	Yes	Yes	No	Yes
Voltage sag compensation	Yes	Yes	No	Yes
Voltage regulation	Yes	Yes	Yes	Yes
Harmonic isolation	Yes	Yes	Yes	Yes
Common DC link	No	Yes	Yes	Yes
Energy storage option	Yes	Yes	Yes	Yes
Fault isolation	Yes	Yes	Yes	Yes
Bidirectional power flow	Yes	No	Yes	No
Control complexity	complicated	Average	Easy	Average
Efficiency	92%	96%	98%	95%
Delivery Year	2009	2012	2011	2012
Application	Smart grid	DC charge station	Substation	Traction

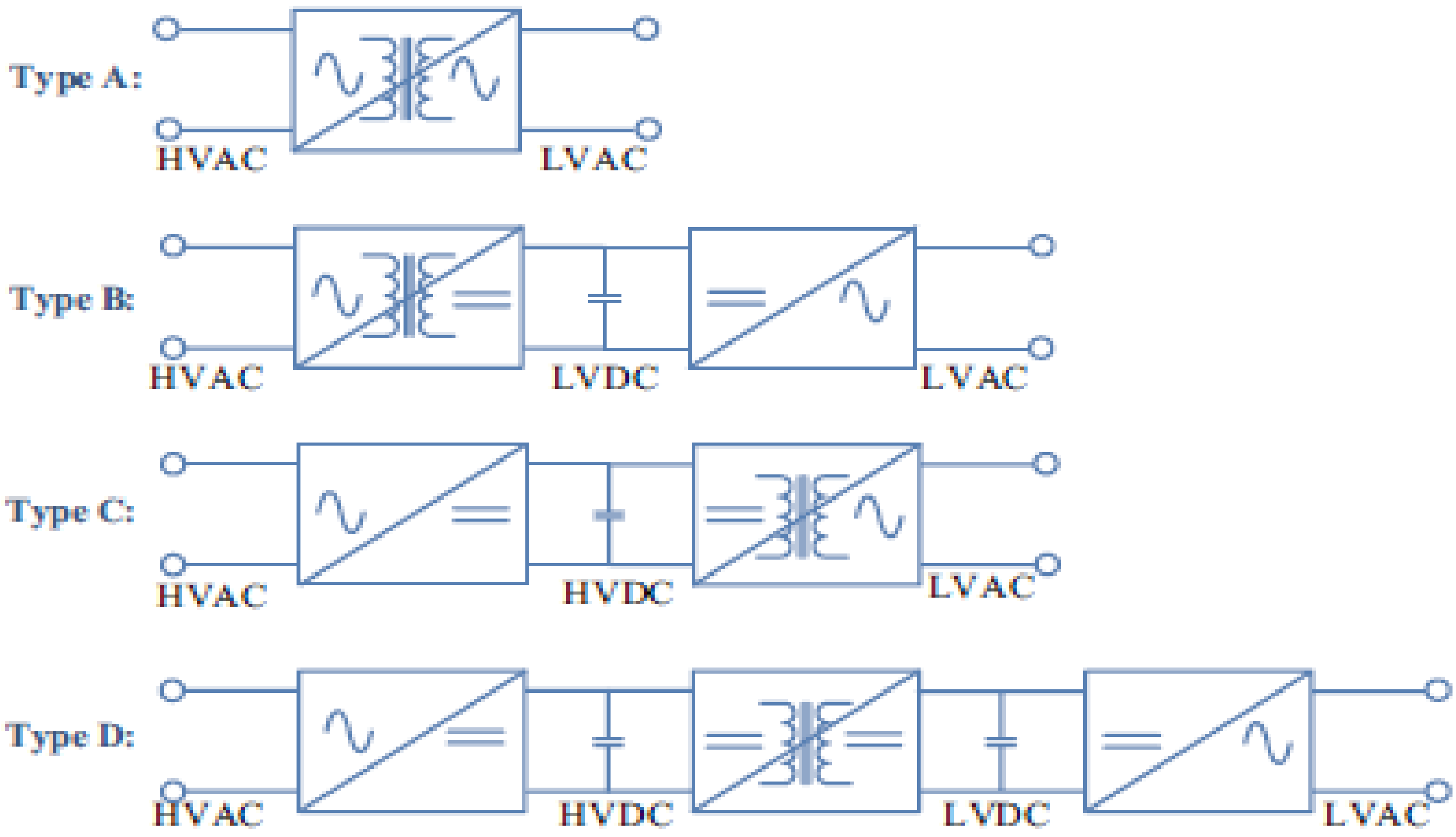
Terminology

- McMurray: Electronic Transformer (1968)
- Brooks: Solid-State Transformer (SST, 1980)
- EPRI: Intelligent Universal Transformer (IUTTM)
- ABB: Power Electronics Transformer (PET)
- Borojevic: Energy Control Center (ECC)
- ETH Zurich: MAGACube
- Wang: Energy Router

2. Architectures & Designing of SST

- Architectures of SST
- Topologies of SST
- Designing of SST

SST Architectures



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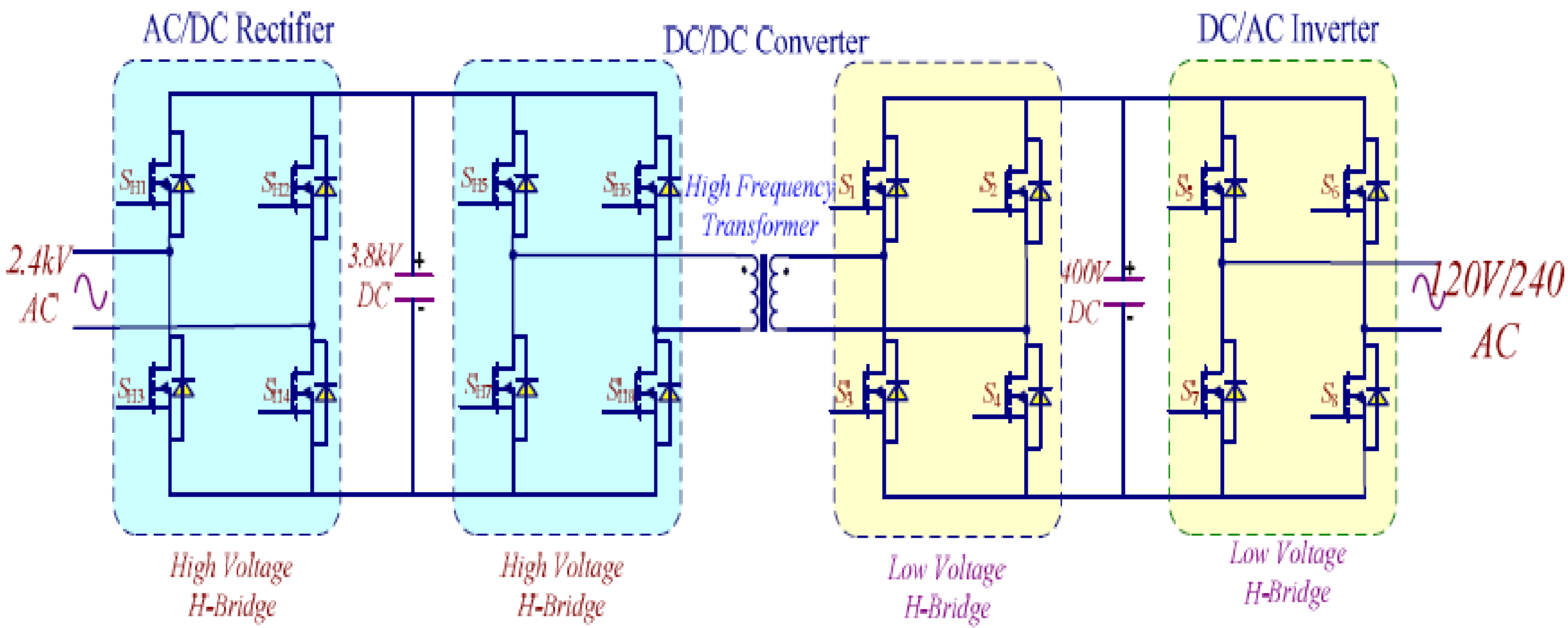
- The most commonly used power electronic converter topology is the two-level converters.



- **Limitations:** Even using the highest available power rating 6.5kV IGBTs, a two-level converter based SST can only interface with 2.4kV AC voltage.

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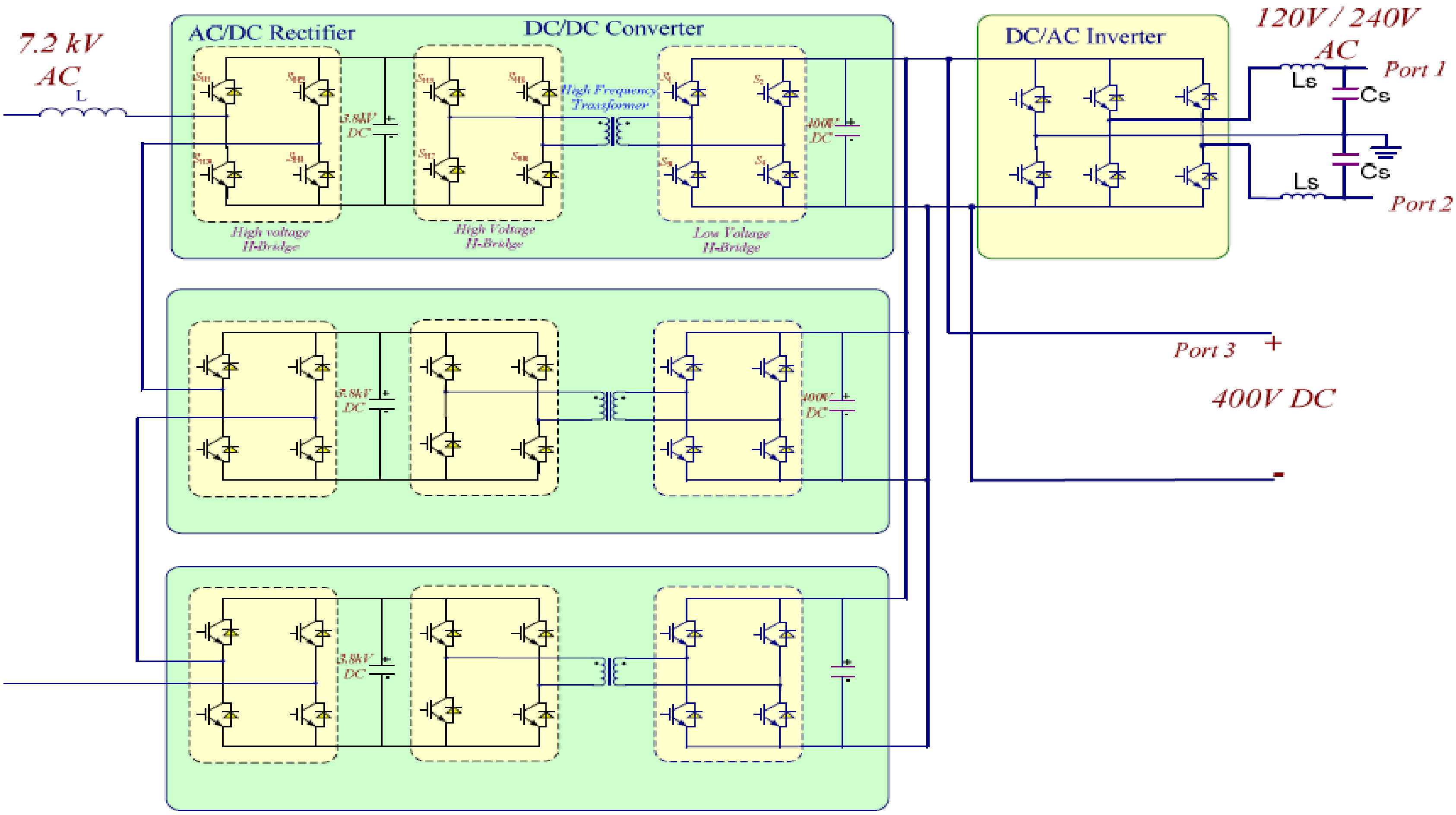
- In order to apply the silicon based SST to a distribution voltage level 7.2kV/12kV, multi-level converter topology is inevitable.



Topologies for AC/DC Stage of SST

- Multilevel Converters have become a big success because of their higher power ratings, lower common-mode voltages, reduced harmonic content, near sinusoidal currents, no or small input and output filter, increased efficiency, possible fault tolerant operation.
- Most popular multilevel converter topologies are:

  i. Neutral Point Clamped or Diode-Clamped Converters

  ii. Flying Capacitor Converters

  iii. Cascade H-Bridge Converters

  iv. H-bridge NPC

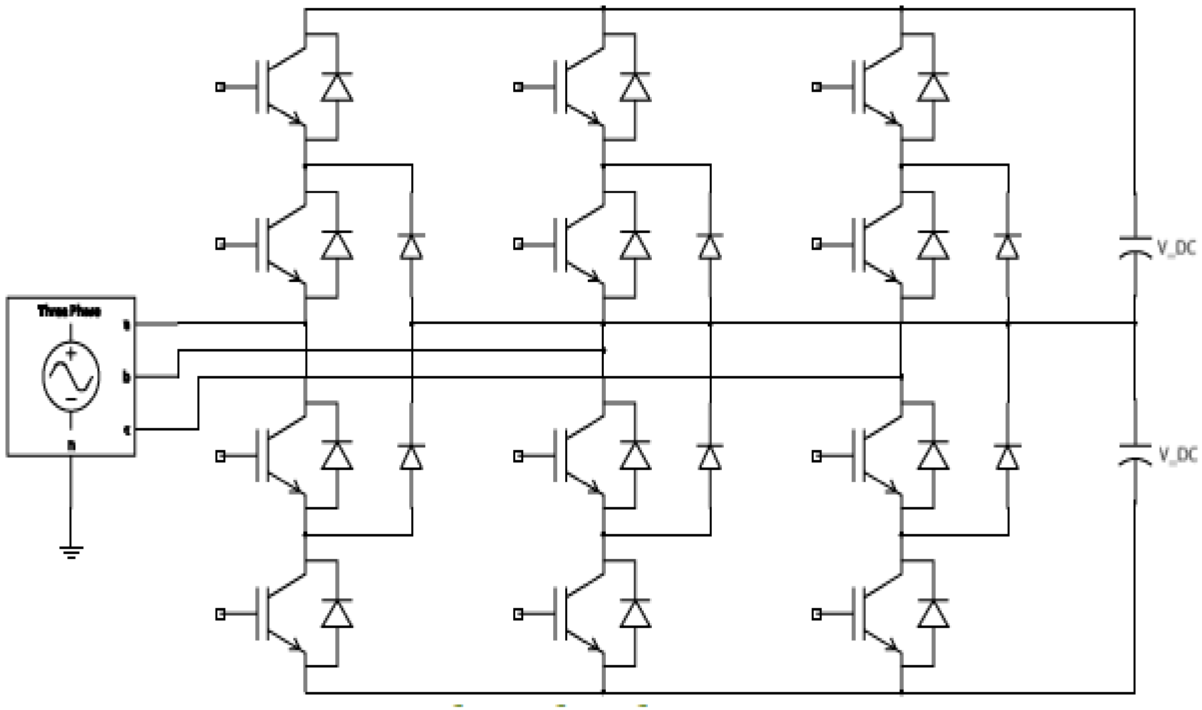
  v. Three-Level Active NPC

  vi. Five-Level Active NPC

  vii. Transistor-Clamped Converter

  viii. Modular Multilevel Converter

i. Neutral Point Clamped or Diode-Clamped Converters



Three Level NPC Power Circuit

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- **Advantages:**
  - All phases share the same DC bus and which reduces the capacitor requirements.
  - The capacitors can be pre-charged as a group.
  - The efficiency of the converter is high when the devices are switched at fundamental frequency.
  - The reactive power flow can be controlled.
  - The control method is simple for back-to-back converters.

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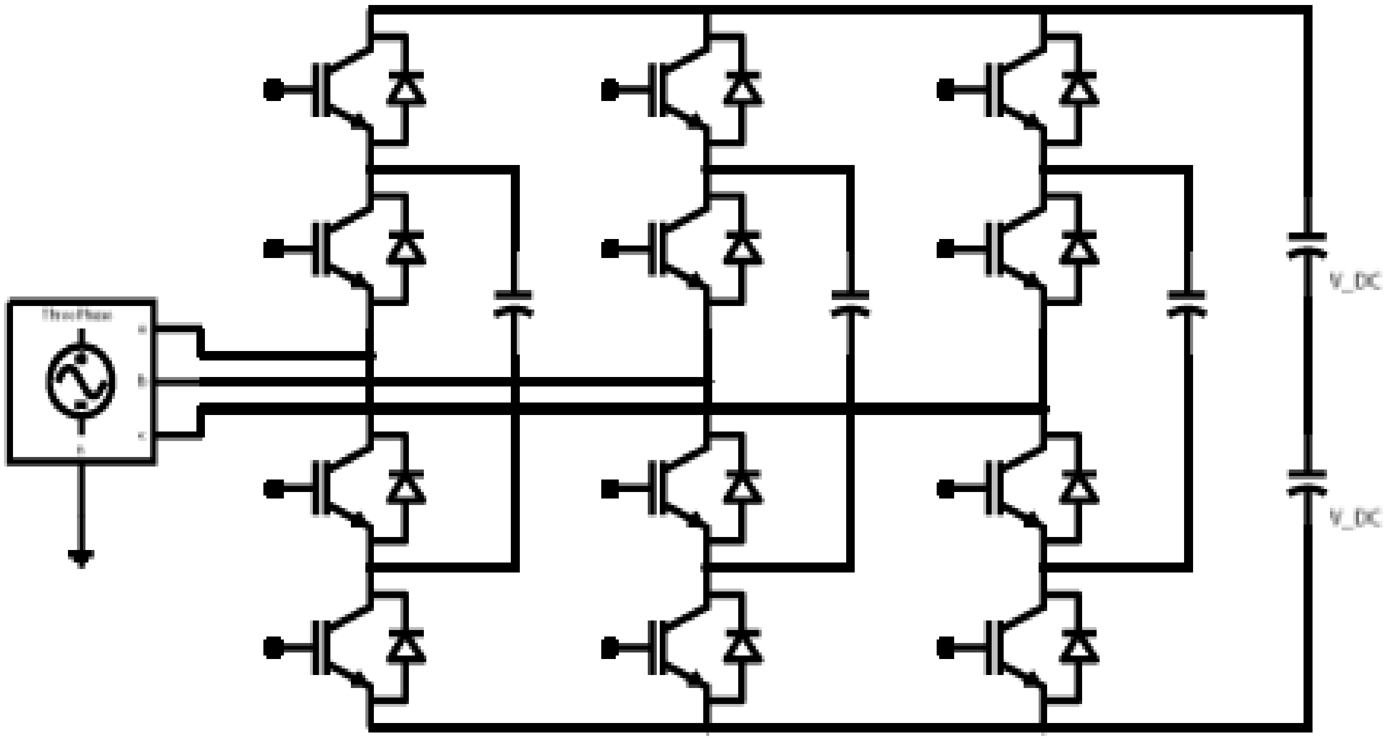
- **Disadvantages:**
  - The real power flow is difficult to control for the individual converter because the intermediate DC levels can lead to an overcharge or discharge of capacitors without precise monitoring and control.
  - The number of clamping diodes increases with the square of the number of voltage levels, which might not be practical for systems with a high number of levels.
  - The current flowing through the switches differs because certain switches conduct for a longer period than others do. When this is not taken into account during the design phase, it can lead to over- or under sizing of switching devices.
  - The uneven current flow also causes uneven losses, which result in unsymmetrical temperature distribution. This affects the cooling system design and limits the maximum power rating, output current and switching frequency of the converter for a specific semiconductor technology

ii. Flying Capacitor Converters



Three Level FC Power Circuit

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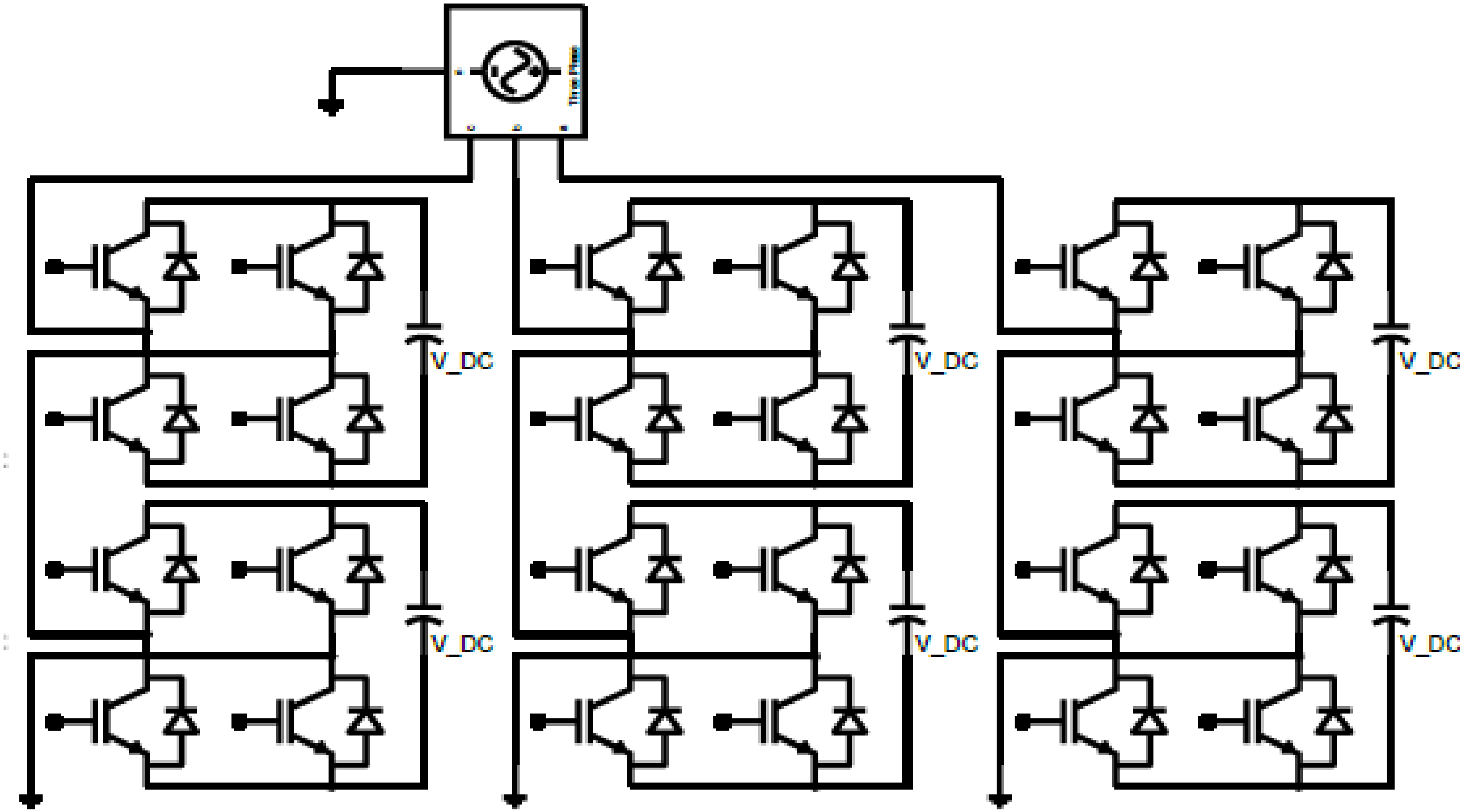
- **Advantages:**
  - The large number of capacitors allows the converter to ride through short outages and deep voltage sags.
  - Both real and reactive power can be controlled.
  - Provides switch combination redundancy for balancing different voltage levels
- **Disadvantages:**
  - High converter levels require a large amount of storage capacitors. Systems with high converter levels are more bulky, expensive and more difficult to package.
  - High switching frequencies are required in order to keep the capacitors balanced, whether self-balancing or a complex control-assisted modulation method is used. These high switching frequencies are not feasible for high power applications.
  - The required pre-charging of the capacitors to the same voltage level at start-up is complex.
  - Switch utilization and efficiency are poor for real power transmission

iii. Cascade H-Bridge Converters



Five Level CHB Converter

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- **Advantages:**
  - The CHB can generate more output voltage levels than the NPC and the FC. This enables the CHB to have lower device switching frequencies for the same output voltage waveform. Lower devices switching frequencies allow for air cooling and higher fundamental output frequency without derating and without the use of an output filter.
  - The topology allows for modularized layout and easy packaging, because each level has the same structure and there are no extra clamping diodes or voltage balancing capacitors.
  - Bulky and lossy snubber circuits can be avoided, since soft-switching is possible with this topology.
  - Automatically balance of the capacitor voltages, since the average charge of each DC capacitor over one line cycle equals zero.
  - When the transformer is equipped with appropriate displacements in the windings, it can result in input-current harmonics reduction.

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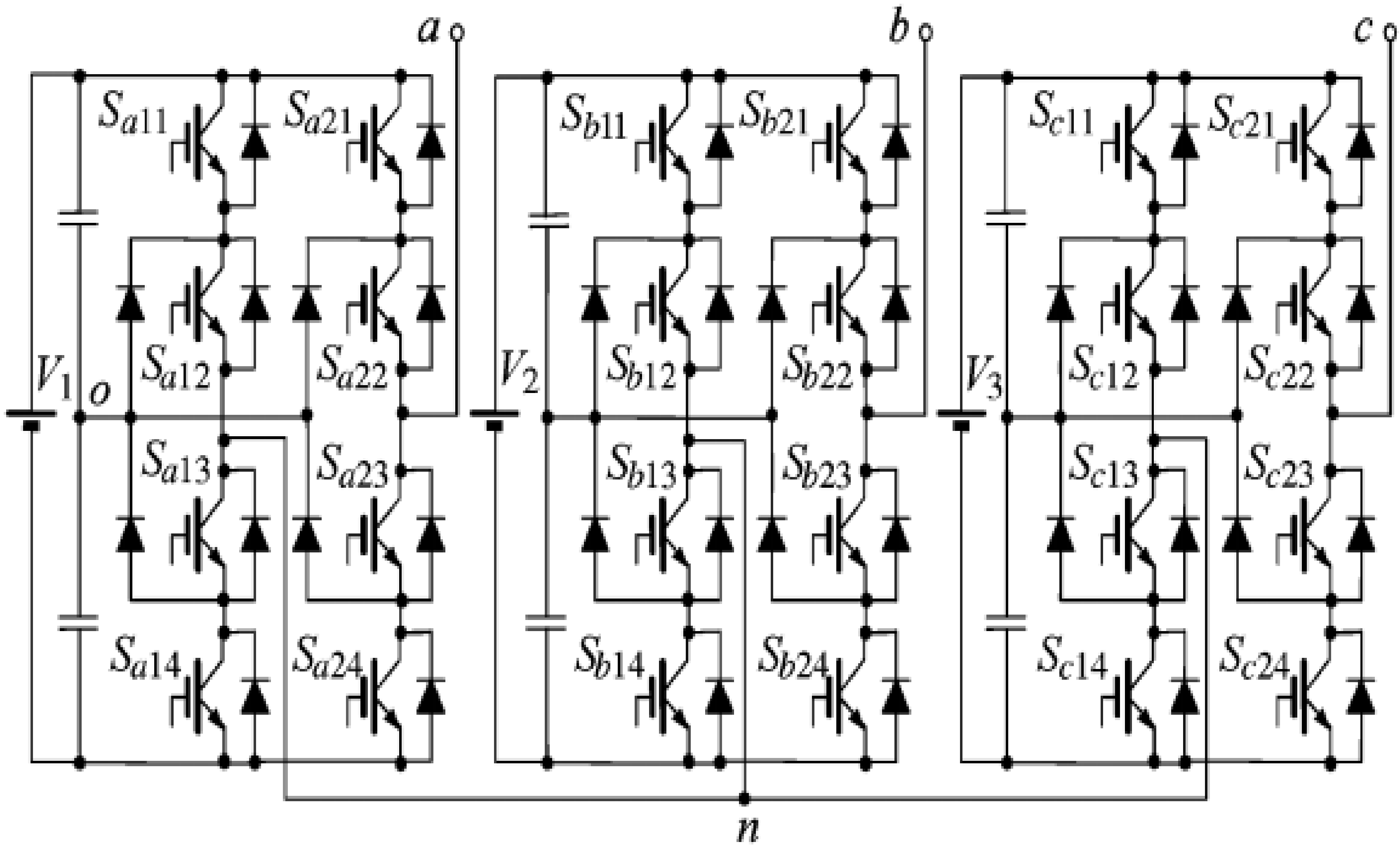
- **Disadvantages:**
  - Each H-bridge requires an isolated voltage source.
  - The maximum DC-link voltage of each H-bridge is limited by the voltage rating of its components. Because of this limitation, the CHB is unable to generate a high voltage DC-link.

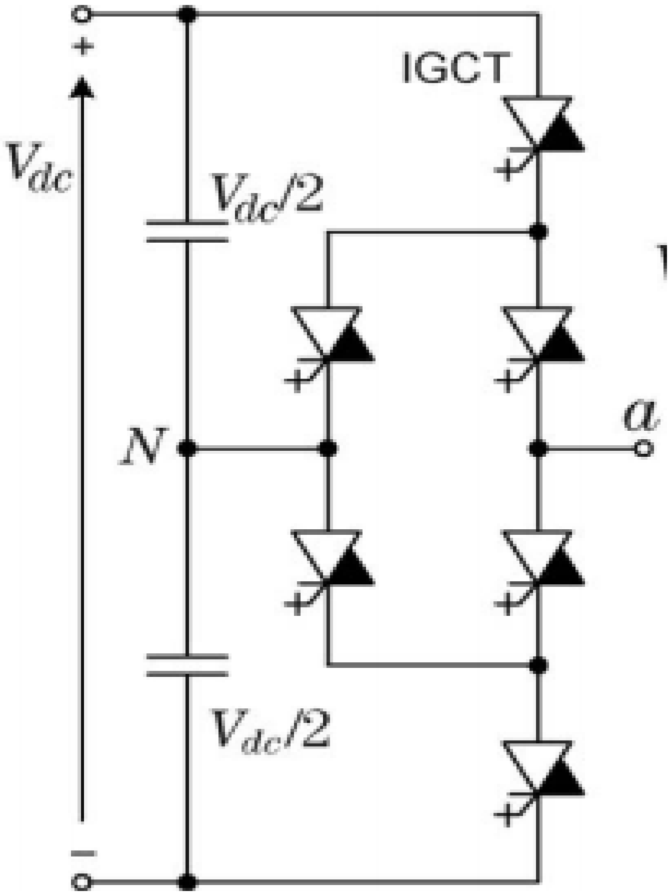
iv. H-bridge NPC



iv. H-bridge NPC

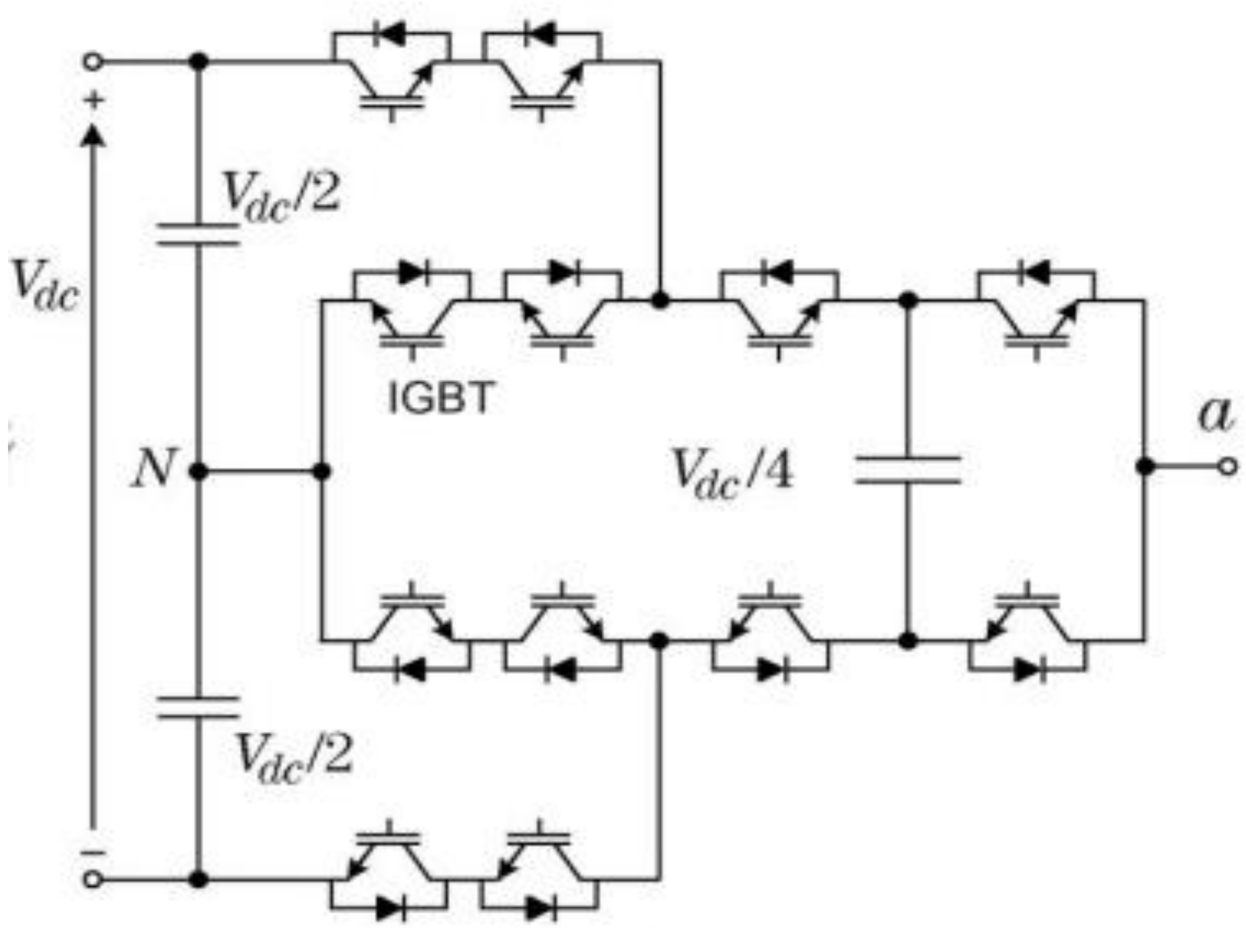
- **Advantages:**
  - The complex transformer is able to effectively cancel low-order harmonics.
- **Disadvantages:**
  - The topology requires a rather complex modulation scheme
  - The control method should be able to balance the DC bus capacitor voltage and the switching loss among the inverter arms
  - This topology is less modular than the CHB topology

v. Three-Level Active NPC



- **Advantages:**
  - This can be used to control the power loss distribution and enables much higher power rates than the normal 3L-NPC.
- **Disadvantages:**
  - Although control of the power loss distribution is better in the 3L-ANPC, it still suffers from the other drawbacks of the conventional NPC

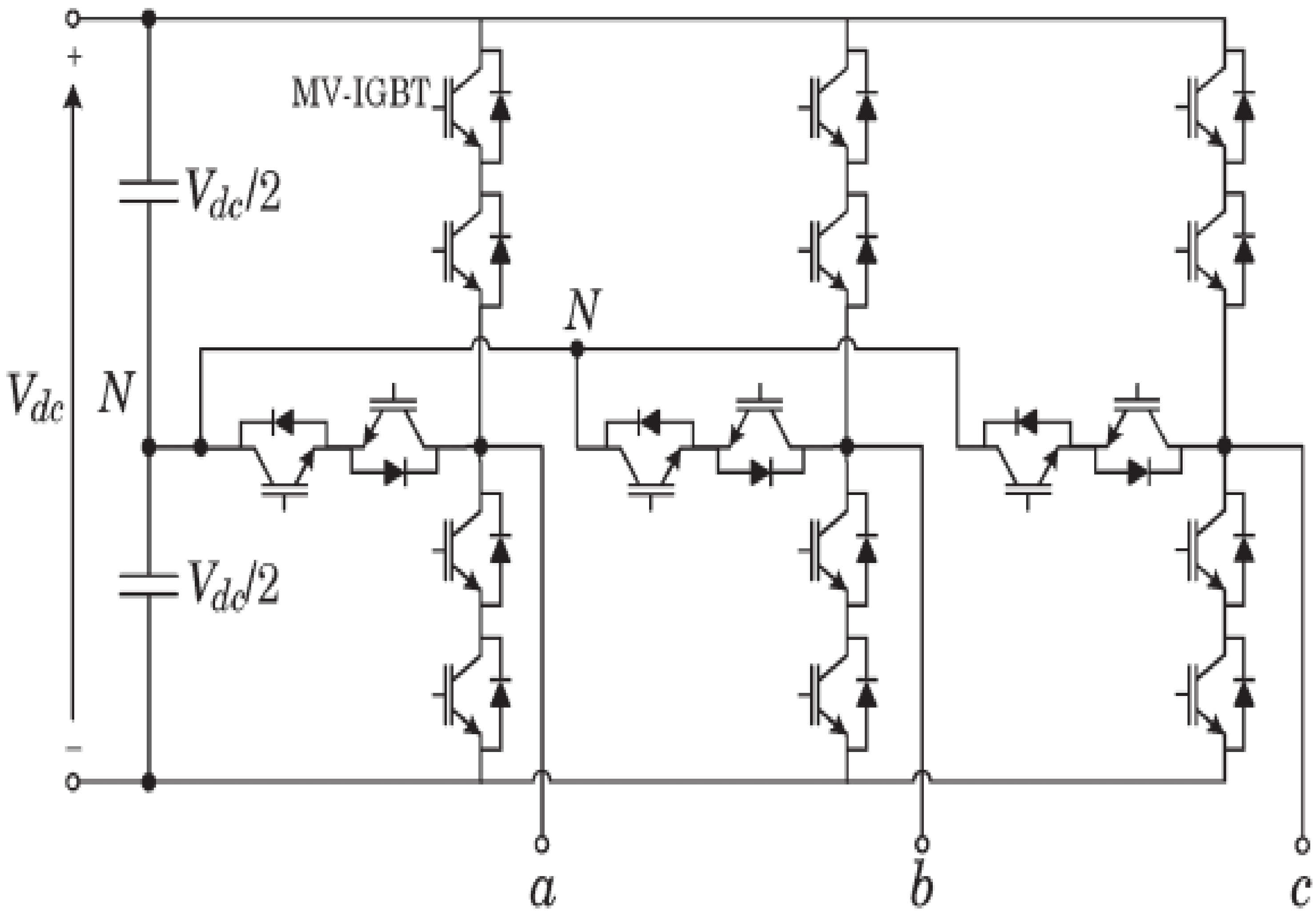
vi. Five-Level Active NPC



Cont…

- **Advantages:**
  - The use of FCs enables modularity; this is not possible with the classic NPC topology
  - Higher voltage levels can be achieved by adding FCs, without the need to add series connected diodes
- **Disadvantages:**
  - The control and circuit structure of the 5L-ANPC are complex.
  - The control scheme needs to be able to handle the FC control and voltage initialization, and the NPC DC-link capacitor voltage.
  - Increasing the number of FCs only increases the number of output voltage levels, not the power rating. This is still limited by the ANPC part of the circuit.

vii. Transistor-Clamped Converter



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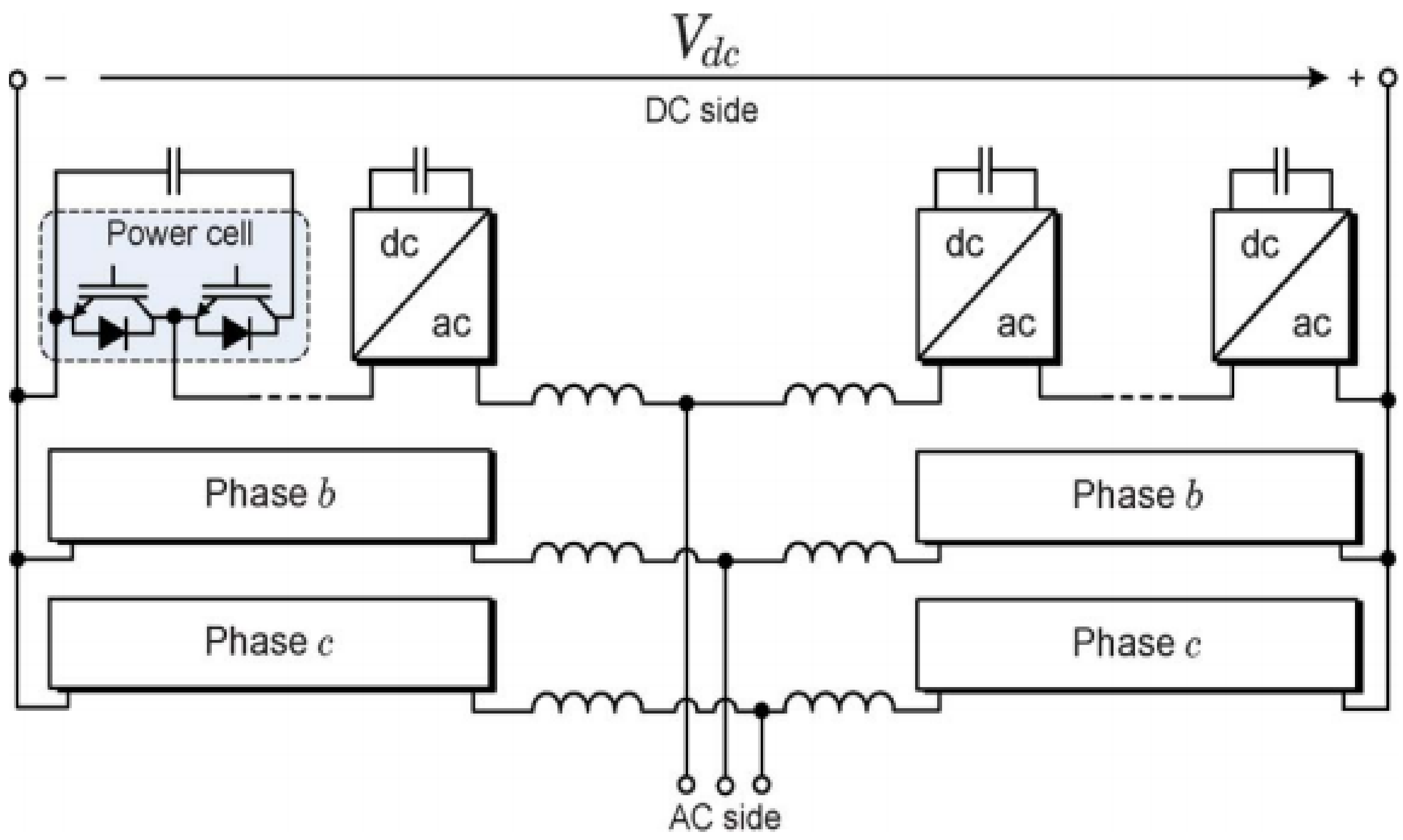
- **Advantages:**
  - The TCC requires only half the amount of switches compared to the NPC and FC.
  - The switches only have to handle half the voltage compared to the NPC. This allows for double the switching frequency and a better output waveform for the same current.
  - Simple control of the gates, because only one power transistor is switched at a time. This results in a direct relation between the transistor which has to be turned on, and the output voltage.
  - Modular design
- **Disadvantages:**
  - A voltage balancing strategy is required.
  - Large number of transistors required.

viii. Modular Multilevel Converter



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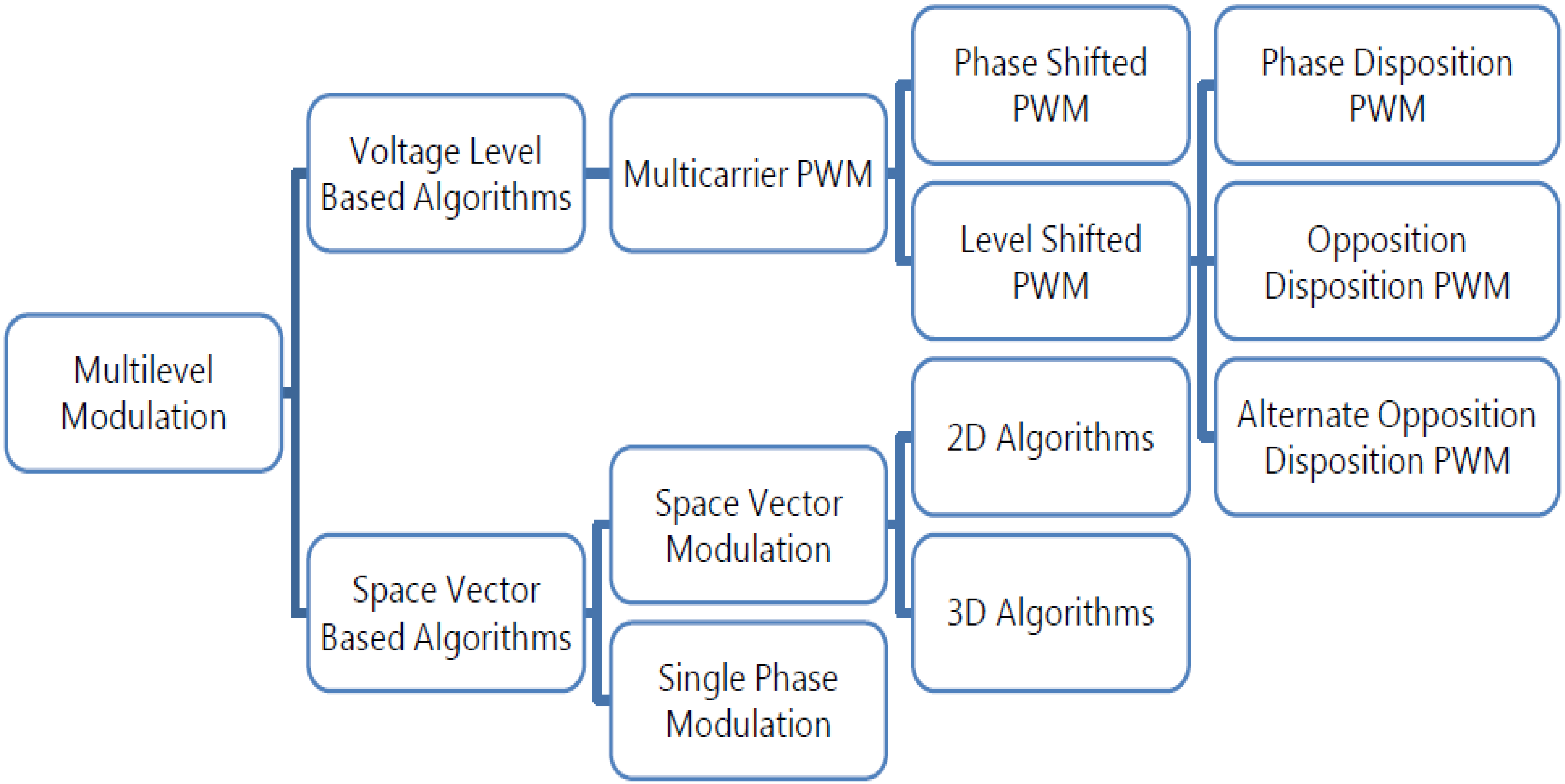
- **Advantages:**
  - The topology is highly modular, flexible, and scalable, making a range from medium-to high-voltage levels possible.
  - It has low harmonic content and low filter requirements.
  - The MMC does not require separate DC sources, eliminating the need for a special transformer.
  - Each module provides its own capacitor and therefore there is no need for high-voltage DC-link capacitors.
  - An increase of levels enables a decrease in module switching frequency without compromising the power quality
- **Disadvantages:**
  - A complex control is required to pre-charge the capacitors and balance the average value of the voltage across each submodule capacitor.

Comparison of Multilevel Topologies

	Control	Voltage Balance Control	Modular	Major Disadvantages
NPC	Simple	Unattainable	No	Voltage balance issues for systems with more than 3 levels
FC	Complex	Complex	Yes	Higher output levels require a large amount of capacitors
CHB	Simple	Simple	Yes	High voltage DC-link not achievable
HNPC	Complex	Complex	limited	Complex control and modulation
3L-ANPC	Complex	Complex	No	Number of clamping diodes increase with square of output levels
5L-ANPC	Complex	Complex	Yes	Complex circuit and control
TTC	Simple	Complex	Yes	Large number of transistors required
MMC	Complex	Complex	Yes	Complex control

Modulation Schemes for AC/DC Stage of SST



Different modulation scheme for multilevel topologies

i. Phase Shifted PWM

- The Phase Shifted PWM (PS-PWM) is a multicarrier-based sinusoidal PWM developed for the control of multi-cell converters like the CHB. Each cell is assigned with two carriers and is modulated independently using the same reference signal. A phase shift across all the carriers is introduced in order to generate the stepped multilevel waveform.
- **Advantages:**
  - The cell switching frequency of an n level converter is n times lower than the converter output frequency.
  - A lower cell switching frequency means that the power electronic devices switch at a lower frequency resulting in fewer losses.
  - PS-PWM causes the power to be evenly distributed among the cells across the entire modulation index. This allows reduction in input current harmonics for the CHB.

ii. Level Shifted PWM

- This modulation technique, where each carrier represents a possible output voltage level of the converter, is known as the Level Shifted PWM (LS-PWM).
- **Advantage:**
  - Better harmonic cancelation properties than the PS-PWM.
- **Disadvantage:**
  - This method results in uneven power distribution among the different cells leading to input current distortion in CHB circuits.

iii. 2D Space Vector Modulation

- The 2D Space Vector Modulation (2D-SVM) works by transferring the three phase voltages of the converter to the α-β plane. The 2D-SVM determines the nearest vector to the reference vector to generate the switching sequence and their duty cycles.
- **Advantage:**
  - The 2D-SVM uses simple calculations.
- **Disadvantage:**
  - This can be used for any three-phase balanced system.

iv. 3D Space Vector Modulation

- The 3D Space Vector Modulation (3D-SVM) is a generalization of the 2D-SVM for unbalanced networks. When the system is in an unbalanced situation, or if a zero sequence or triple harmonics are present in the system, the state vectors are no longer located in the α-β plane. In order to calculate the state vectors under these conditions, the α-β plane is extended into the third dimension with a γ axis.
- **Advantage:**
  - The 3D-SVM is useful for compensating the zero sequence in active power filters, in systems with or without neutral unbalanced loads or triple harmonics and for balancing DC-link capacitor voltages.
- **Limitation:**
  - This method is applicable as a modulation technique for all applications that provide a 3D vector control.

v. Single Phase Modulation

- A rather new modulation technique is the Single Phase Modulation (1DM). The 1DM uses a simple algorithm to determine the switching sequence and corresponding times. It does this by generating the reference phase voltage as an average of the nearest phase-voltage levels.
- **Advantages:**
  - The computational costs of the 1DM are low
  - Independent of the number of levels and its performance is equivalent to that of 2D-SVM and 3D-SVM.
  - The 1DM is independent of the chosen topology
- **Disadvantages:**
  - Requires post processing to select one stage between the possible redundant states.

Comparison of Multilevel Modulation Techniques

	Algorithm	Hardware Requirements	Remarks
PS-PWM	Simple	Minimal	Each cell is assigned with a pair of carriers, allowing for easy control
LS-PWM	Simple	Minimal	Slightly better harmonic cancelation
2D-SVM	Complex	Extensive	Only applicable for balanced 3 phase networks
3D-SVM	Complex	Extensive	Suitable for balanced and unbalanced 3 phase networks with or without neutral
1DM	Simple	Extensive	Independent of topology and number of phases

Topologies of DC/DC Stage of SST

- The possible candidate topologies for the DC-DC converter of the SST are:

  i. Single-phase Dual Active Bridge converter

  ii. Three-phase Dual Active Bridge converter

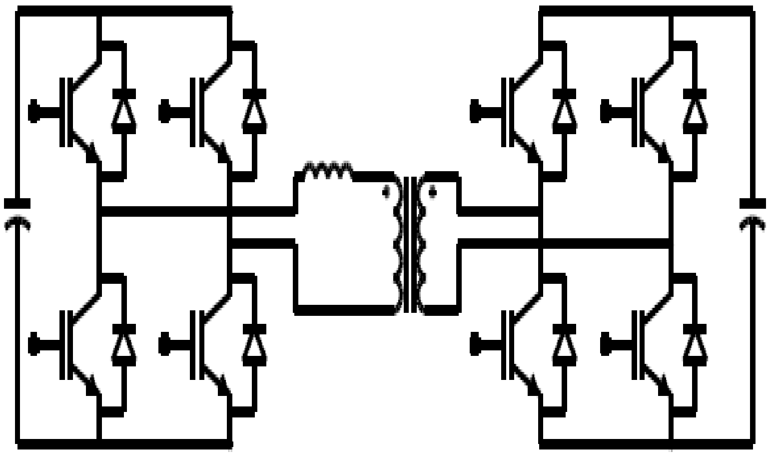
  iii. Bidirectional Isolated Full Bridge converter

  iv. Bidirectional Isolated Current Doubler converter

  v. Bidirectional Isolated Push-Pull converter

  vi. LLC converter

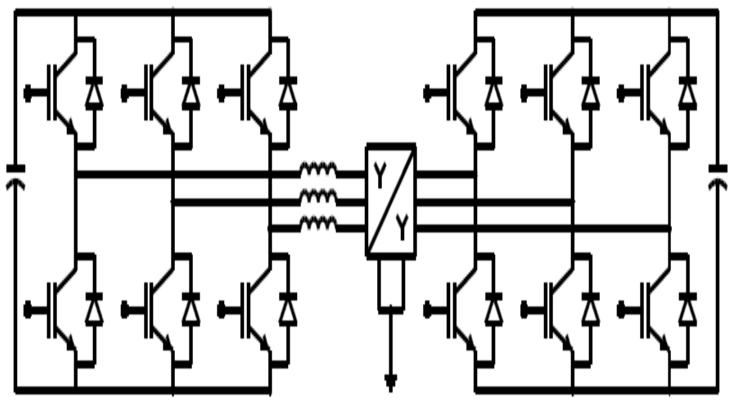
i. Single Phase Dual Active Bridge Converter



- The Single-phase Dual Active Bridge (DAB) converter consists of a full bridge circuit on the primary and the secondary side, with a HF transformer in between. The DAB utilizes the leakage inductance of the transformer to provide energy storage and to modify the shape of the current waveform.

- **Advantages:**
  - The major advantages of the DAB are the low number of passive components, evenly shared currents in the switches and soft switching properties.
- **Disadvantage:**
  - Depending on the modulation scheme and operating voltage, large RMS currents can flow through the DC capacitors, especially on the secondary side.

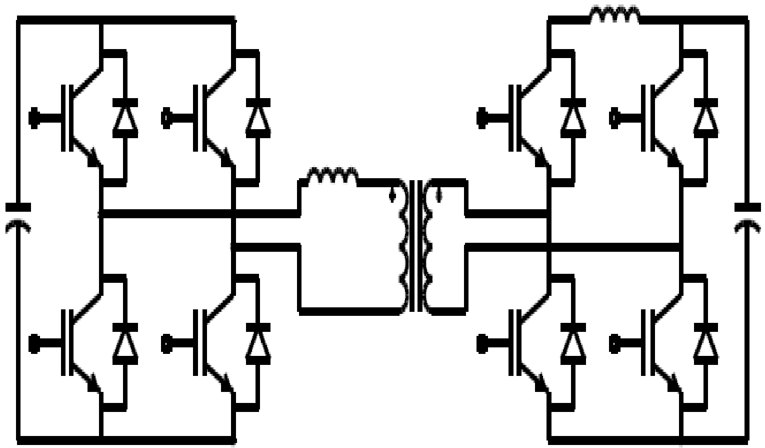
ii. Three Phase Dual Active Bridge Converter



- The Three-phase Dual Active Bridge consists of three half bridges on both the primary and secondary side. It requires three inductors for energy storage and three HF transformers; although a single three-phase, HF transformer can be used instead.

- **Advantages:**
  - It achieves good overall efficiency and requires lower ratings for the transformer, switches and inductors compared to the DAB.
  - This topology also has smaller RMS capacitor currents and component ratings than the DAB.
- **Disadvantage:**
  - The number of power semiconductor devices needed is very high: it requires 12 switches.
  - High conduction and switching losses when operated within wide power and voltage ranges.

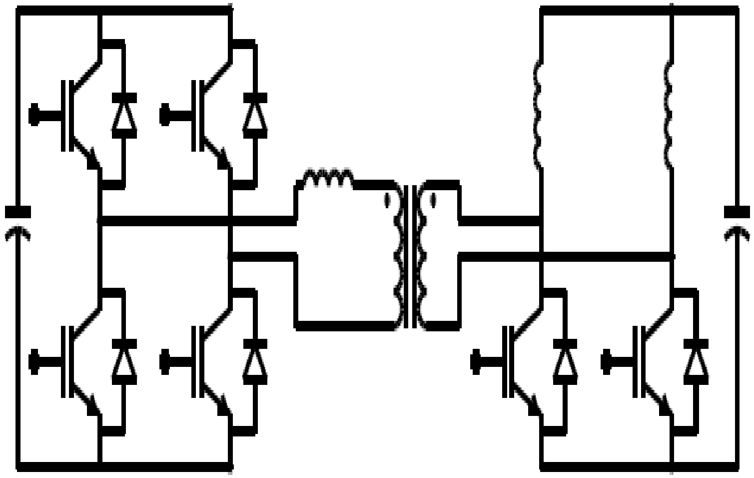
iii. Bidirectional Isolated Full Bridge Converter



- The Bidirectional Isolated Full Bridge converter contains a full bridge with a capacitive filter (voltage sourced) on the primary side and a full bridge with inductive filter (current sourced) on the secondary side.

- **Advantages:**
  - This topology allows high switching frequency, which results in a high power density.
- **Disadvantage:**
  - Additional volume is required for the inductor on the secondary side.
  - Another disadvantage is the requirement of a snubber circuit to avoid voltage spikes during switching. These spikes occur because the switches on the secondary side repeatedly connect the inductor on the secondary side to the stray inductance of the transformer.

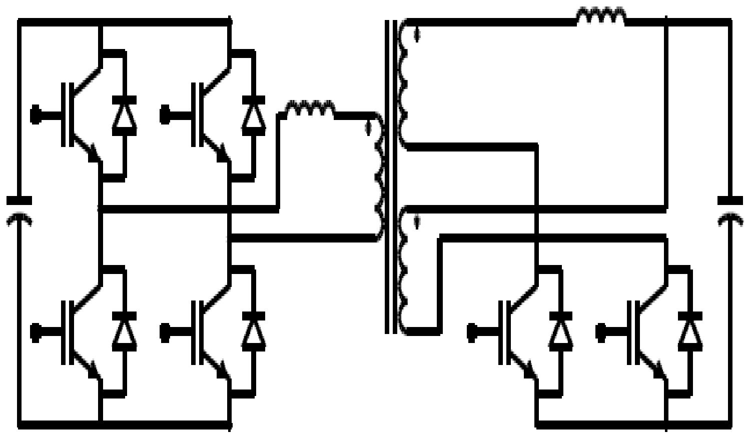
iv. Bidirectional Isolated Current Doubler Converter



- A variation of the bidirectional isolated full bridge converter is the Bidirectional Isolated Current Doubler converter. This topology replaces the two upper switches of the full bridge.

- **Advantages:**
  - This topology replaces the two upper switches of the full bridge on secondary side with inductors. These inductors enable high current handling capabilities and a reduction in conduction losses.
- **Disadvantage:**
  - Requires a transformer with larger power rating. It also requires two large inductors for the secondary side.

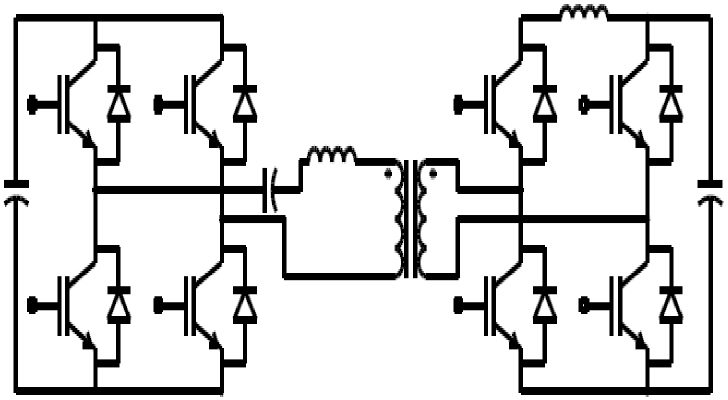
v. Bidirectional Isolated Push-Pull Converter



- The Bidirectional Isolated Push-Pull converter is another variation of the bidirectional isolated full bridge converter. It has a center-tapped transformer with two windings on the secondary side and one output inductor.

- **Advantages:**
  - The output inductor operates at double the switching frequency of the semiconductor, which results in half the inductance requirement of bidirectional isolated current doubler topology.
- **Disadvantage:**
  - Since each winding only conducts during half the switching period, the transformer is ineffectively utilized and requires a higher power rating.

vi. LLC Converter



- The LLC is a resonant DC-DC converter. Resonant converters generate nearly sinusoidal transformer currents.

- **Advantages:**
  - Resonant converters generate nearly sinusoidal transformer currents. This results in low switching losses, which allows higher switching frequencies and higher power densities.
  - The LLC converter has a capacitor in series with the transformer leakage inductance, which blocks DC and prevents saturation of the HF transformer.
- **Disadvantage:**
  - The main disadvantage is that the actual switching frequency varies strongly with the supplied voltage and load. This even leads to an uncontrollable situation in the case of no load, since that situation requires infinite switching.

Comparison of DC-DC Stage Topologies

	Advantages	Disadvantages
Single-phase Dual Active Bridge converter	-Fewest passive components -Good efficiency	-Large RMS DC capacitor currents may occur
Three-phase Dual Active Bridge converter	-Smaller RMS current than DAB -Lower component ratings -No need for extra inductors	-Requires large number of switches and inductors -Higher losses
Bidirectional Isolated Full Bridge converter	-High switching frequency and power density	-Requires extra inductor -Requires snubber circuit
Bidirectional Isolated Current Doubler topology	-High current handling and lower conduction losses -Fewer switches required	-Requires two extra inductors -Limited operating voltage
Bidirectional Isolated Push-Pull topology	-High current handling with reduced inductor requirements -Fewer switches required	- Ineffective use of complex transformer
LLC converter	-Higher switching frequency and power density -Good efficiency	-Large inductor and capacitor required -Uncontrollable at no load

Modulation Schemes for DC/DC Stage of SST

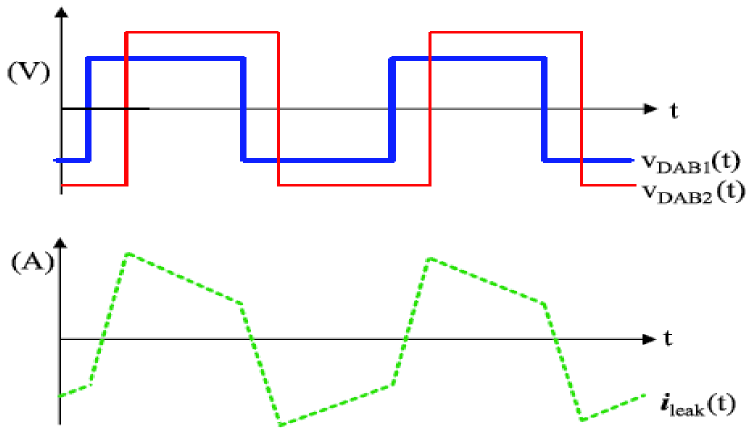
- The main modulation methods that are applied for the DAB are:

  i. Phase Shift Modulation

  ii. Trapezoidal Modulation

  iii. Triangular Modulation

i. Phase Shift Modulation



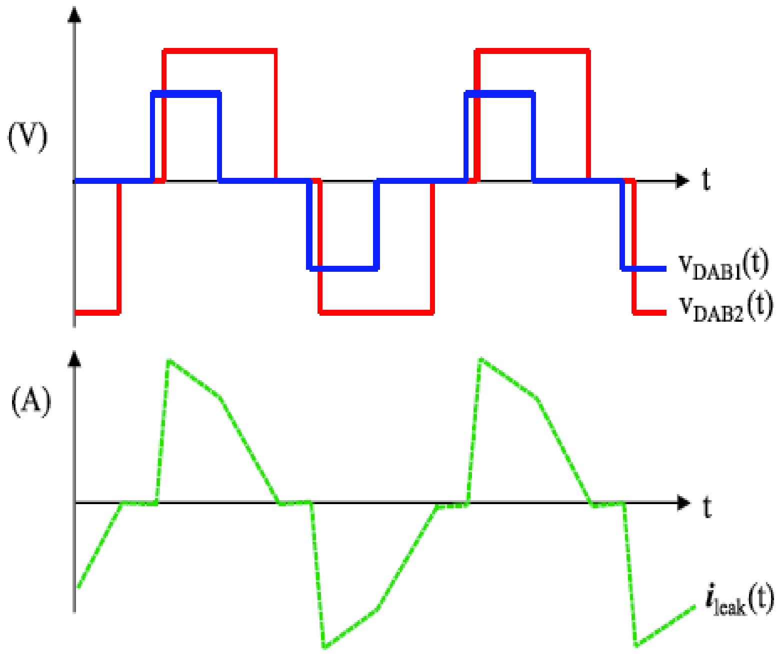
Phase Shift Modulation

- The Phase Shift Modulation, also known as the Rectangular Modulation works by switching the primary and the secondary side at a duty cycle of 50%. The power transfer between both sides can be controlled by adjusting the angle between the primary and secondary switching waveform.

Cont…

- **Advantages:**
  - Low control complexity
  - Lowest RMS circuit current compared to the other two modulation methods
  - Highest power transfer possible
  - Symmetrical share of the losses on all switches
  - Zero voltage switching (ZVS) during turn-on of the switches
- **Disadvantages:**
  - Eight commutations have to be preformed
  - Negative current on the DC side reduces power transfer, this results in a lower efficiency
  - High losses are caused by reactive power when no active power is transferred
  - Turn-off of switches happens under non-zero-voltage conditions, which result in switching losses

ii. Trapezoidal Modulation



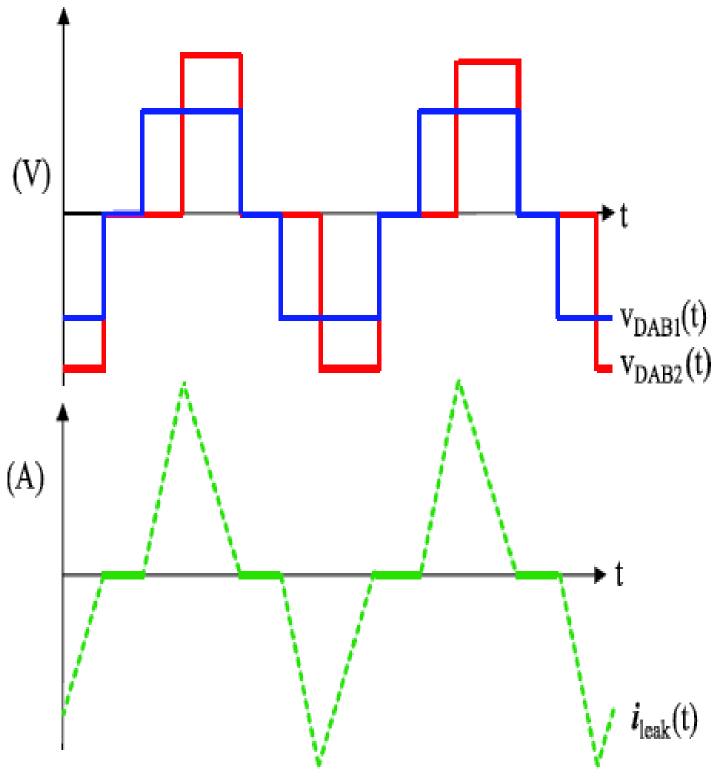
Trapezoidal Modulation

- The Trapezoidal Modulation method is able to reduce the turn-off switching losses by adding a blanking time to the primary switching voltage. This causes half the number of switches (four switches) to switch-off under zero-voltage conditions. However, adding this blanking time requires a higher RMS current in order to transfer the same amount of power, which results in higher conduction losses.

Cont…

- **Advantages:**
  - Lower switching losses.
  - Usable for a larger voltage range.
- **Disadvantages:**
  - Higher conduction losses
  - Unsymmetrical losses if the primary voltage differs from the secondary voltage
  - Complicated modulation and control algorithm
  - Unable to operate under no-load conditions

iii. Triangular Modulation



Triangular Modulation

- A special case of trapezoidal modulation is the Triangular Modulation method.
- This method uses the blanking time or the phase shift to cause one edge of the primary switching voltage to overlap with the secondary. This results in a triangular transformer current, with only two switches turning off under non-zero-voltage conditions. This allows further reduction of the turn-off losses, however, the conduction losses increase due to a larger current peak.

Cont…

- **Advantages:**
  - Lowest switching losses compared to the other two methods
  - Very suitable when the primary and secondary voltage ratios are different from the transformer turns-ratio.
- **Disadvantages:**
  - The switching losses always occur in the same two switches
  - Inefficient use of the period for power transfer
  - Complicated modulation and control algorithm
  - Highest RMS current compared to the other two methods

Comparison of DAB Modulation Techniques

	Major Advantage	Major Disadvantage
Phase Shift Modulation	Simple control and algorithm	Higher losses at low power levels
Trapezoidal Modulation	High voltage range	Unable to operate under no-load
Triangular Modulation	Low switching losses	High RMS currents

Topologies for DC/AC Stage of SST

- Based on the required functions, the possible DC-AC topologies are:

  i. Three Half-Bridges Converters in parallel

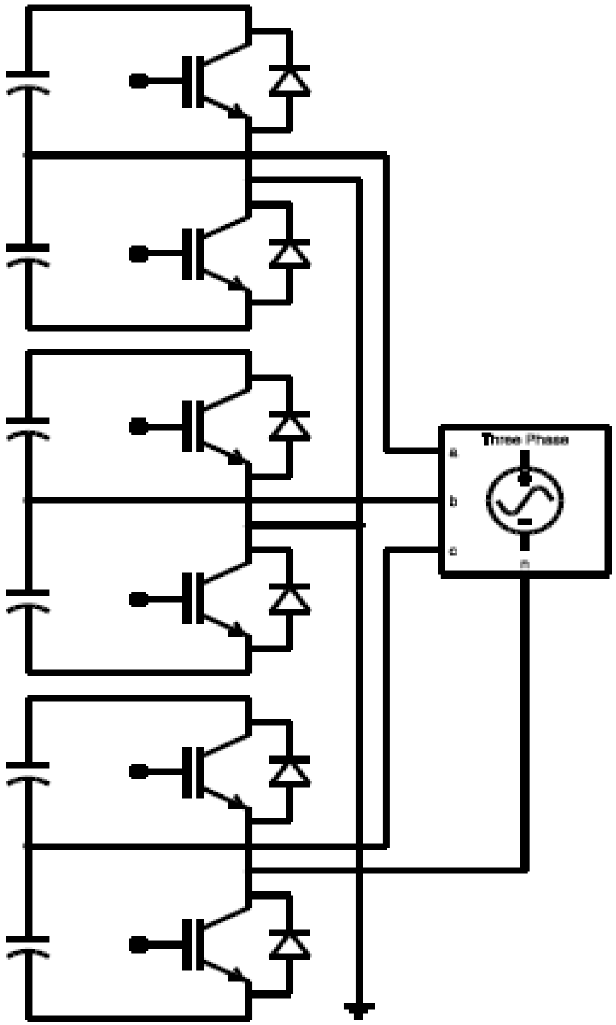
  ii. Three Full-Bridges Converters in parallel

  iii. Three Single-Phase Three-Wire Converters in parallel

  iv. Conventional Three-Phase Converter

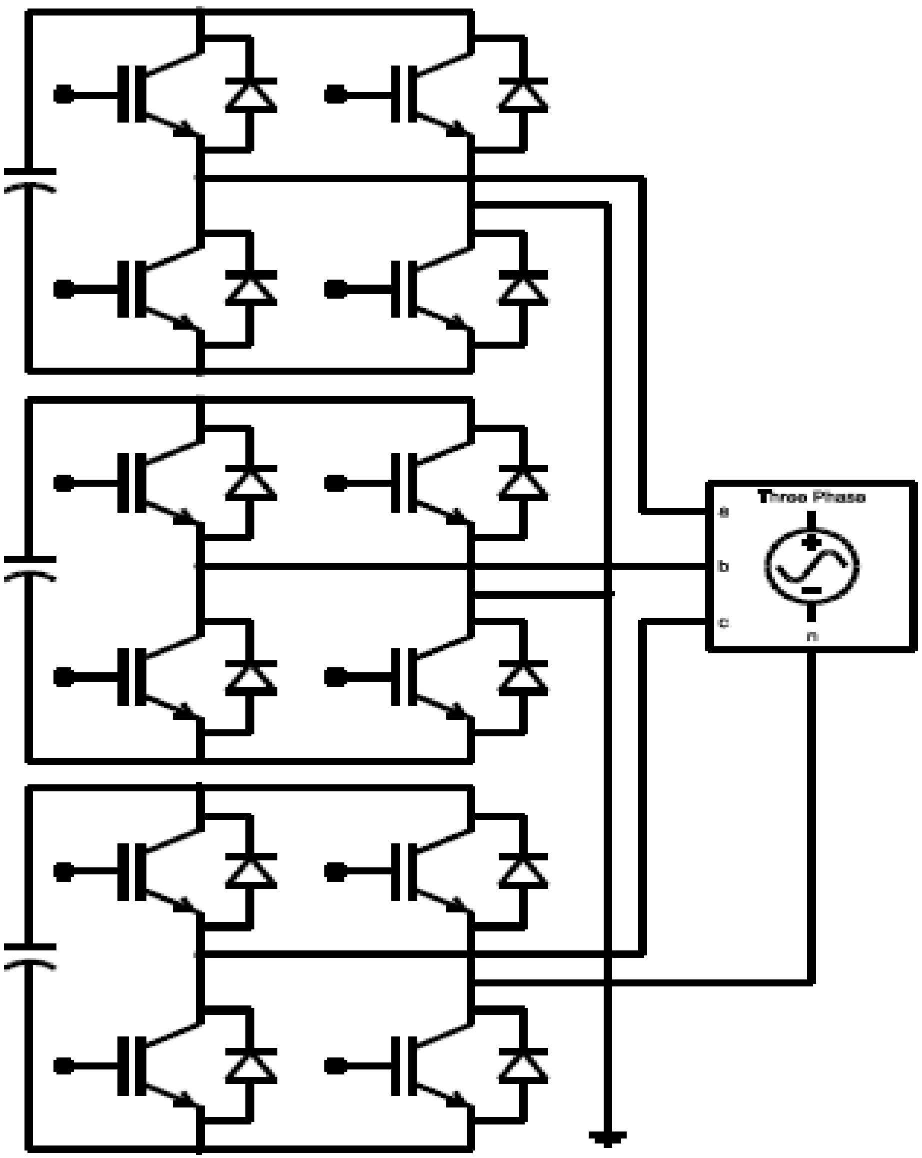
  v. Three-Phase Four-Leg Converter

i. Three Half-Bridges Converters in parallel



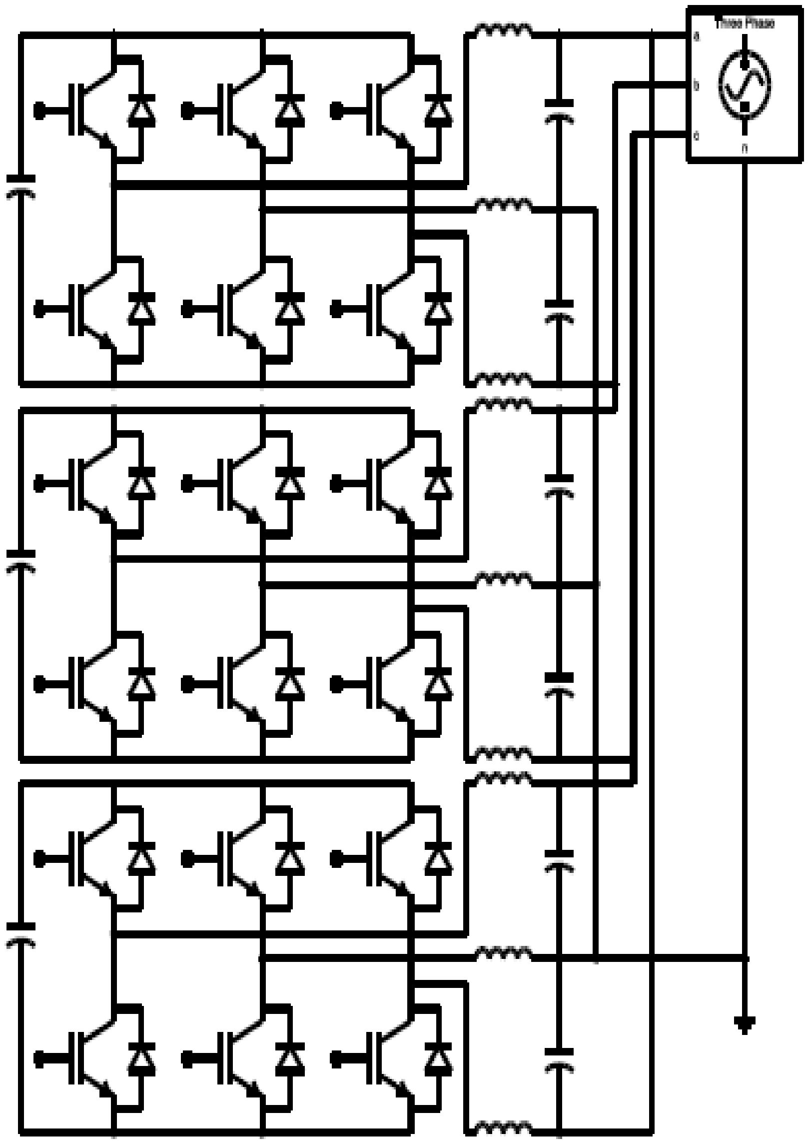
The Half-Bridge Converter is the basic block of the voltage source DC-AC converters. It is build up out of two bidirectional switches. Each switch consists of a controllable power semiconductor device and an antiparallel diode

ii. Three Full-Bridges Converters in parallel



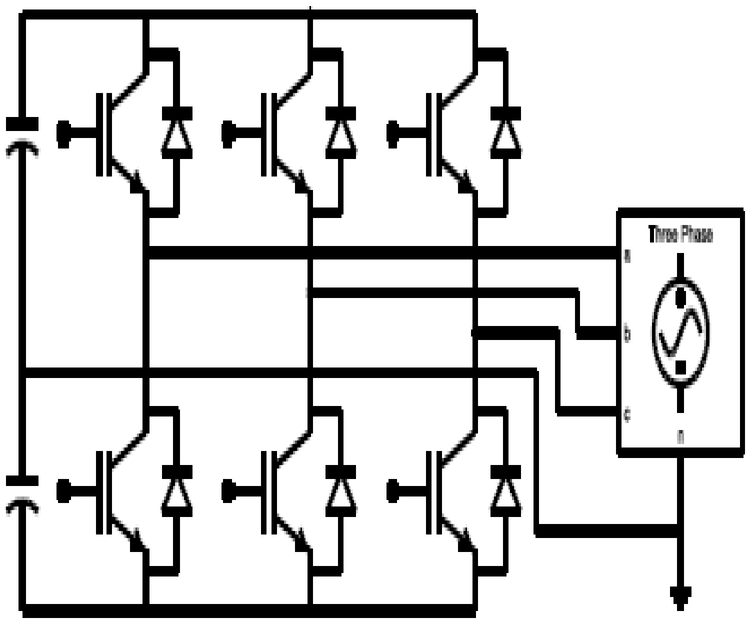
- Each phase of the Full-Bridge (also called H-Bridge) Converters consist of two half-bridge converters
- An advantage with the Full-Bridge Converter is that it requires a lower DC-link voltage than the other topologies.

iii. Three Single-Phase Three-Wire Converters in parallel



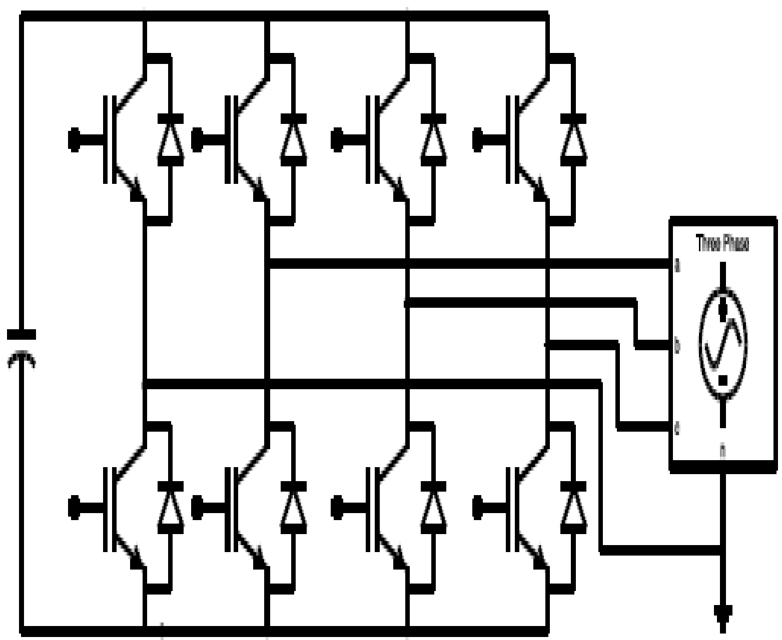
- The Single-Phase Three-Wire (1ϕ3W) Converter uses a combination of three half-bridges and LC output filters to generate two line-to-line and line-to-neutral voltages.
- From its schematic, it becomes clear that this topology requires a lot more components than the previous topologies.
- The addition of the extra switching leg makes this topology capable of handling unbalanced loads.
- Like the previous single-phase converters, the 1ϕ3W also requires a separate converter cell for each output phase.

iv. Conventional Three-Phase Converter



- The Conventional Three-Phase Converter consists of three parallel-connected half-bridge converters. Each half-bridge (also called phase-leg) generates an output voltage, which is shifted with 120owith respect to its predecessor.
- This topology does not require a separate DC source for each phase, which is an advantage, compared to the single-phase topologies.

v. Three-Phase Four-Leg Converter



- One problem faced with the conventional three-phase converter is the unequal voltage sharing between the capacitors. This requires large DC-link capacitors or an extra voltage balancing control scheme.
- The Three-phase Four-Leg (3P4L) Converter overcomes this problem by adding another switching leg.
- The addition of the fourth leg allows control over the neutral current, which results in a lower DC-link voltage and lower RMS capacitor current.
- A drawback is that this topology requires a much more complicated control scheme.

Comparison of DC-AC Stage Topologies

	Switches	Main advantage	Main disadvantage
Half-Bridge	6	Low number of switches	Voltage unbalance issues
Full-Bridge	12	Lowest DC-link voltage	
1ϕ3W	18	Can handle unbalanced loads	Large number of switches
3 phase converter	6	Simple circuit and control	DC-link unbalance
3P4L	8	Can handle unbalanced loads	Complex control

Modulation Scheme for DC/AC Stage of SST

- The three major modulation methods available for the 3P4L converter are:
  - 3D Space Vector Modulation
  - Continuous Pulse Width Modulation
  - Discontinuous Pulse Width Modulation

3D Space Vector Modulation

- The 3D Space Vector Pulse Width Modulation (3D-SVPWM) is an extension of the 2D space vector modulation. The 3D-SVPWM method generates an output voltage vector based on a combination of the phase-to-neutral and zero vector in abc or in the αβγ coordinates.
- **Advantages:**
  - The selection of the output vector allows a good compromise between switching losses and harmonic content.
- **Disadvantages:**
  - This method is requires complex calculations and therefore requires a lot of computation power.

Continuous Pulse Width Modulation

- The Continuous Pulse Width Modulation (CPWM) is an adaptation of the CPWM for three-leg inverters. The PWM signals are generated by comparing the phase-voltages and the neutral phase-voltage to a triangular carrier waveform.
- **Advantages:**
  - The simple algorithm of the CPWM allows for easy implementation with very low hardware requirements.
- **Disadvantages:**
  - Compared with other modulation methods, CPWM may result in higher switching losses.
  - The implementation of CPWM shows that this method only requires the conventional abc duty cycle in order to generate the IGBT gate signals.

Discontinuous Pulse Width Modulation

- The Discontinuous Pulse Width Modulation (DPWM) uses discontinuous waves. During each carrier cycle one phase ceases modulation and its associated phase is clamped to the positive or negative DC value.
- **Advantages:**
  – This enables the generation of an output with low switching losses and low distortion at high line-voltages.
- **Disadvantages:**
  – Most DPWM methods require the phase angle of the output voltage or current, thus resulting in a more computational intense system.

Comparison of DAB Modulation Techniques

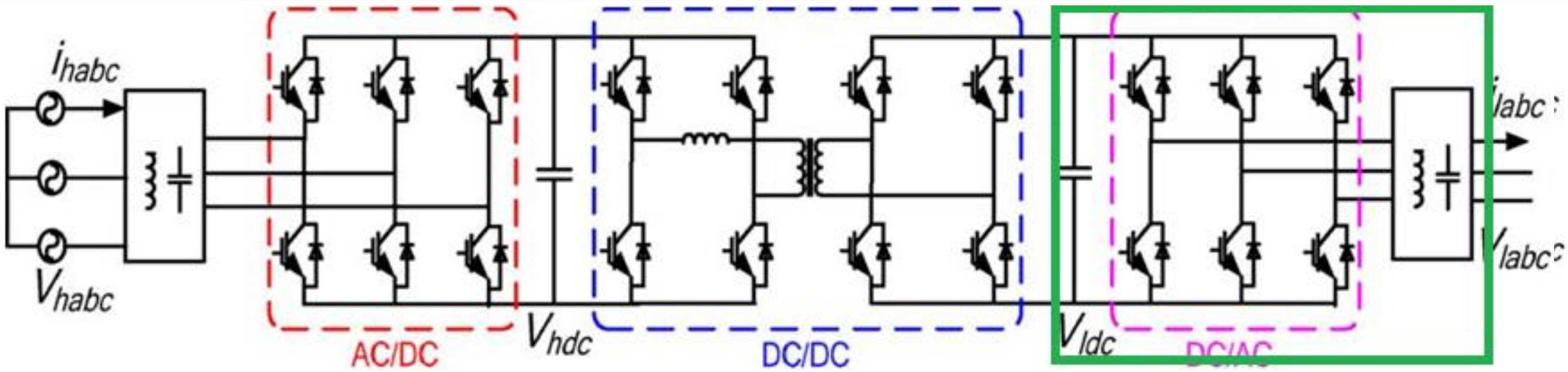
	Implementation	Switching losses
3D-SVPWM	Complex	Modest
CPWM	Easy	Modest
DPWM	Complex	Low

Overall SST Topology & Modulation Scheme

Stages	Topology	Modulation Technique
AC-DC Stage	Cascade H-Bridge Converters	Phase Shifted PWM
DC-DC Stage	Single Phase Dual Active Bridge Converter	Phase Shift Modulation
DC-AC Stage	Three-Phase Four-Leg Converter	Continuous Pulse Width Modulation

Optimum SST Topology and Modulation Scheme

Design of SST Parameters



SST

- **AC/DC Stage**
  - Rectifier Stage
  - HVDC Bus
  - Input Filter
- **DC/DC Stage**
  - DAB Converter
  - Transformer
  - Filter Capacitance
- **DC/AC Stage**
  - Inverter Stage
  - Output Filter
  - LVDC Bus

Design Issues of SST components

- Requirements:
  - Fast dynamic response
  - Bidirectional Power Flow.
  - IEEE compliant harmonic content

- Assumptions:
  - The components are lossless.
  - The switches turn on and turn off instantaneously
  - Passive components operate in a linear region so that saturation can be avoided.

Design of Parameters for AC/DC Stage

- This stage acts as rectifier when to transfer power from high voltage side to low voltage side and acts as inverter to transfer power from low voltage side to high voltage side. To design this stage the designing of the following parameters are important which are as follows:
  - No. of Cascaded Stages
  - DC link Voltage.
  - DC link capacitance value
  - Carrier Frequency and Filter Inductor

Cont…

- **No. of Cascaded Stages:**
  - The no. of cascaded H-bridge stage depends upon the maximum voltage level of DAB stage. This number of modules is calculated by the following equation:

$$N_m = ceil\left(\frac{100 * \sqrt{2} * V_{ph-PCC}}{95 * DAB_{max}}\right)$$

Where, N_m = Number of cascaded H-bridge module

$V_{ph\text{-}PCC}$ = Phase voltage of PCC

DAB_{max} = max voltage level of one DAB stage = $\frac{80}{105}\% * V_{IGBT}$

and ceil is the the function that round the value between the brackets towards the next highest integer.

- **DC link Voltage:**

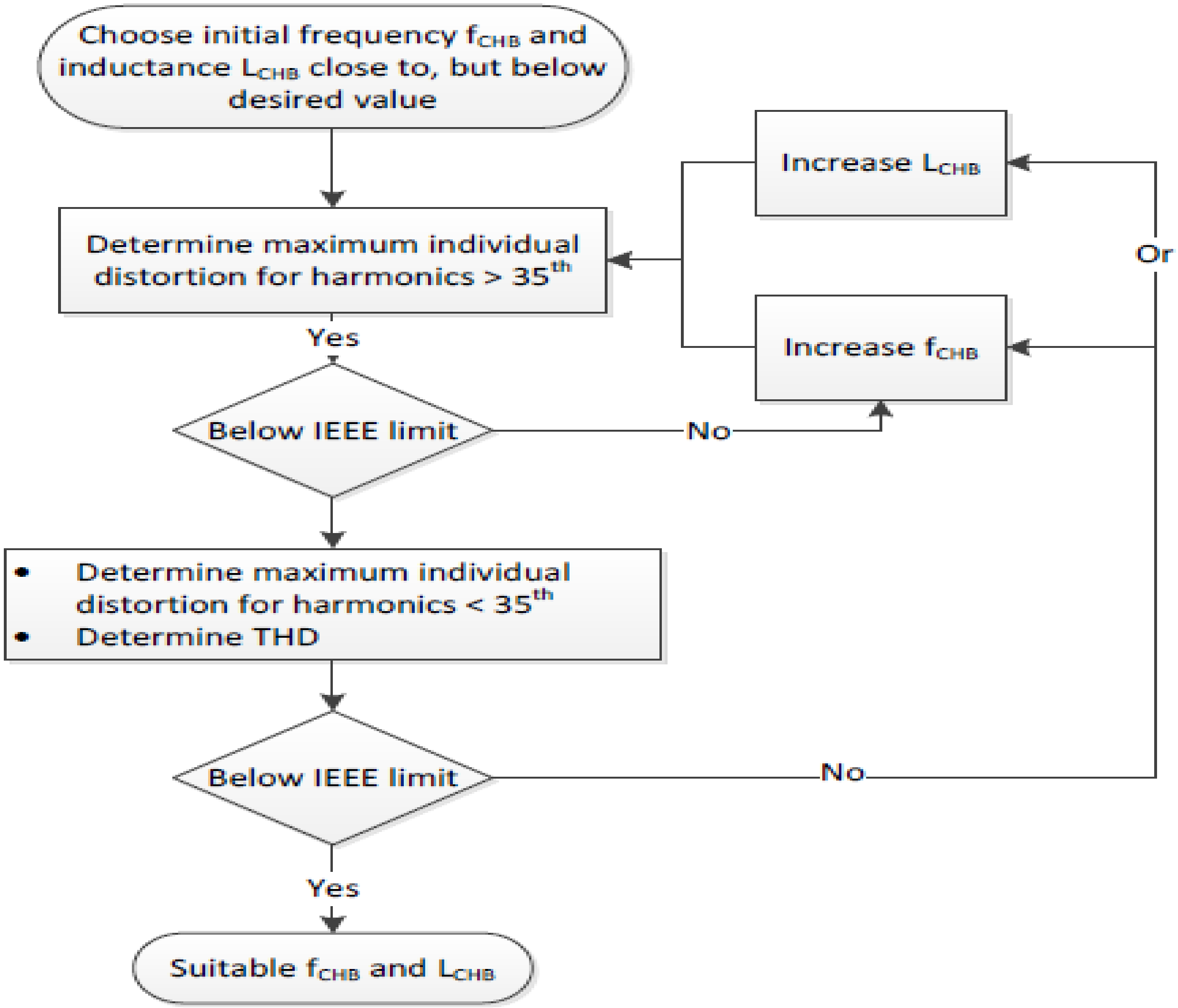
$$V_{DC} = \sqrt{2}V_{PCC}/M$$

- **DC link capacitance value Capacitor Value:** $C_{min} = \frac{P}{2 * \Pi * f * V_{DC} * \Delta V}$

Cont…

- **Carrier Frequency and Filter Inductor:**
  - The values of the carrier frequency $f_{CH,}$ Band filter inductor L_{CHB} are determined based by the harmonic distortion caused by the CHB. A higher carrier frequency results in lower harmonic distortion, but also increases the switching losses. A higher inductance L_{CHB} reduces the harmonic distortion, but at the same time increases the inductor size, cost and the voltage drop over that inductor. Keeping in mind about the IEEE harmonic level the carrier frequency and filter inductor is chosen by the following algorithm

Cont…



Algorithm to Select Carrier Frequency And Filter Inductor

Design of Parameters for DC/DC Stage

- The Dual-Active Bridge is used to achieve galvanic isolation between the high and low-voltage side of the SST. It consists of a DC/AC-AC/DC converter with a high-frequency transformer in between. The number of DAB modules is equal to the number of H-Bridges in the CHB. Each DAB module is connected to a single H-Bridge from the CHB.
- The outputs of the DABs are all connected to a DC-bus. The design approach for the parameters required to create a DAB model are as follows:
  - Transformer turns-ratio
  - Switching Frequency
  - Leakage Inductance
  - Filter Capacitor

Cont…

- **Transformer turns-ratio:**

$$n_{Tr} = \frac{V_{DAB1}}{V_{DAB2}}$$

Where,

V_{DAB1} = High Voltage side DAB voltage

V_{DAB2} = Low voltage side DAB Voltage

- **Switching Frequency:**
  - An optimal switching frequency can be chosen based on the transformer characteristics, switching devices and desired efficiency. Generally use a switching frequency of 20 kHz. This frequency is used for power ratings from 1kW to 1MW

- **Leakage Inductance:**

$$L_{DAB} = \frac{n_{Tr} * V_{DAB1} * V_{DAB2}}{2 * f_{DAB} * P_{DAB}} * D_{DAB}(1 - D_{DAB})$$

- **Filter Capacitor**

$$C_{DAB1} = \frac{50 * P_{DAB-rated}}{{V_{DAB1}}^2 * f_{DAB}} \qquad C_{DAB2} = \frac{50 * P_{DAB-rated}}{{V_{DAB2}}^2 * f_{DAB}}$$

Design of Parameters for DC/AC Stage

- The DC-AC stage takes the DC voltage from the DAB and converts it into an AC voltage. On the AC-side, the converter can be connected either to a LV-grid while operating in grid connected mode, or to a load while operating in standalone mode. The design approaches of the important parameters of this stage are as follows:
  - DC Link Voltage
  - Switching Frequency and Grid Filter Values

Cont…

- **DC Link Voltage:**
  - The relationship between the ac output voltage and DC voltage is:

$$V_{DAB2} \geq \sqrt{3} * \sqrt{2} * V_{ac}$$

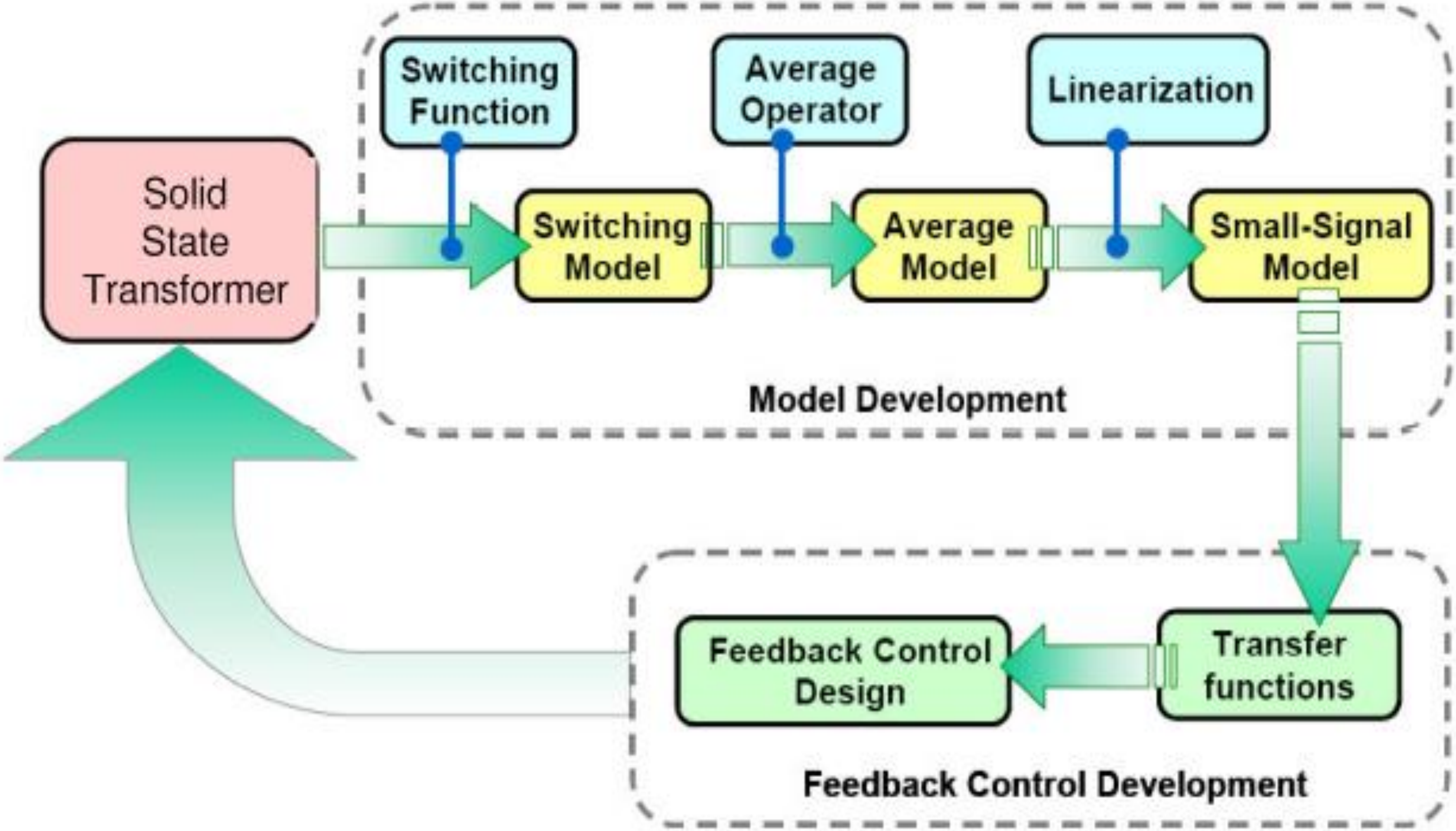
The capacitor in the LCL-filter of the converter causes a voltage drop. This voltage drop should be less than 10% of the grid voltage. A margin of 5% below the DC-link voltage is reserved for the DC-link capacitor ripple. Considering the both margins, the minimum DC link voltage is:

$$95\% * V_{DAB2-min} = \sqrt{3} * \sqrt{2} * 110\% * V_{Ph-WIND}$$

3. Modeling of Solid State Transformer

- Modeling of SST
- Designing of Controllers for Each Stage of SST

Modeling Approach of SST



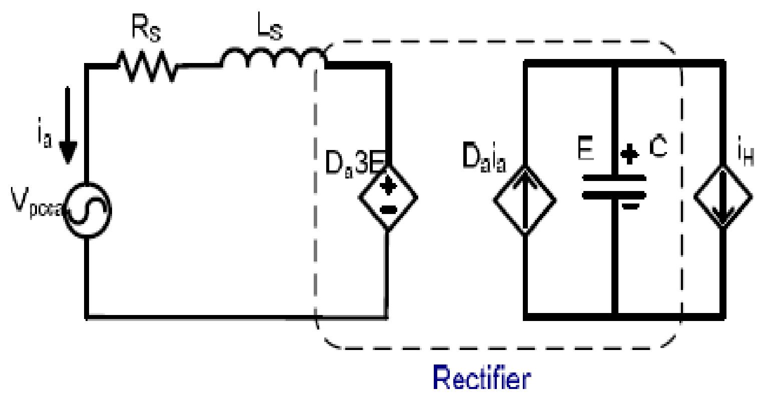
Stage by stage Modeling Approach of SST

Modeling of AC/DC Stage of SST

- The AC/DC rectifier converts the single phase or three phase AC voltage to three DC output while maintaining unity power factor at the input side. The differential equations of the rectifier are:

$$\frac{d\vec{i}_g}{dt} = \frac{3E}{L_s}\vec{d}_h - \frac{\vec{V}_{pcc}}{L_s} - \frac{R_s}{L_s}\vec{i}_g$$

$$\frac{dE}{dt} = -\frac{E}{R_L C} - \frac{\vec{d}_g^T \vec{i}_g}{2C}$$



Average Model of Rectifier

Where,

$$\vec{i}_g = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \vec{d}_h = \begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix}, \vec{V}_{pcc} = \begin{bmatrix} V_{pcca} \\ V_{pccb} \\ V_{pccc} \end{bmatrix}$$

Cont…

- The single phase d-q transformation is applied to the equations and the differential equations in d-q coordinates are derived by applying the following transformation equation

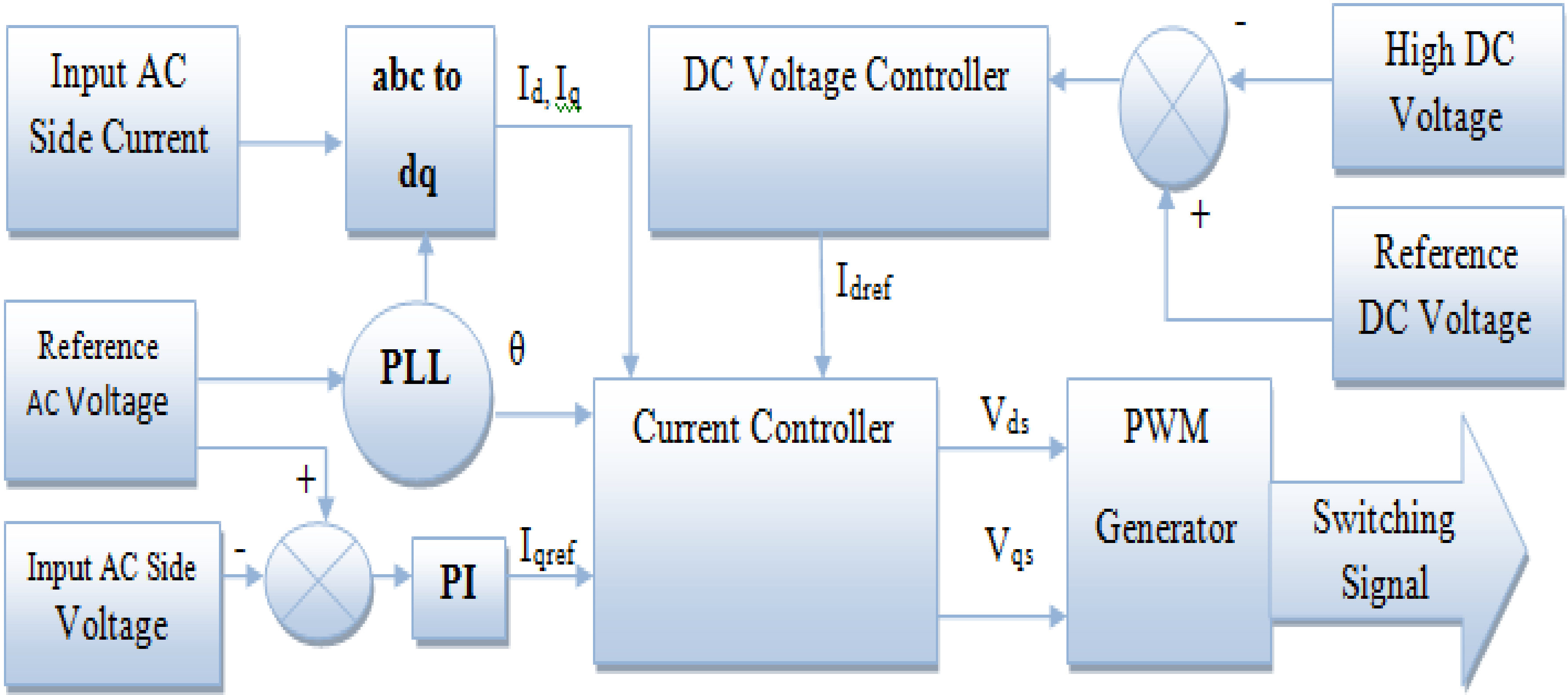
$$[x]_{dq} = [T].[x]_{am}$$

- The d-q axis equations are

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{3E}{L_s}\begin{bmatrix} d_d \\ d_q \end{bmatrix} - \frac{1}{L_s}\begin{bmatrix} v_{pccd} \\ v_{pccq} \end{bmatrix} - \begin{bmatrix} \frac{R_s}{L_s} & -\omega \\ \omega & \frac{R_s}{L_s} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$\frac{dE}{dt} = -\frac{E}{R_L C} - \frac{1}{2C}\begin{bmatrix} d_d \\ d_q \end{bmatrix}^T \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

Control Technique for AC/DC Stage of SST



Rectifier Stage Controller Overview

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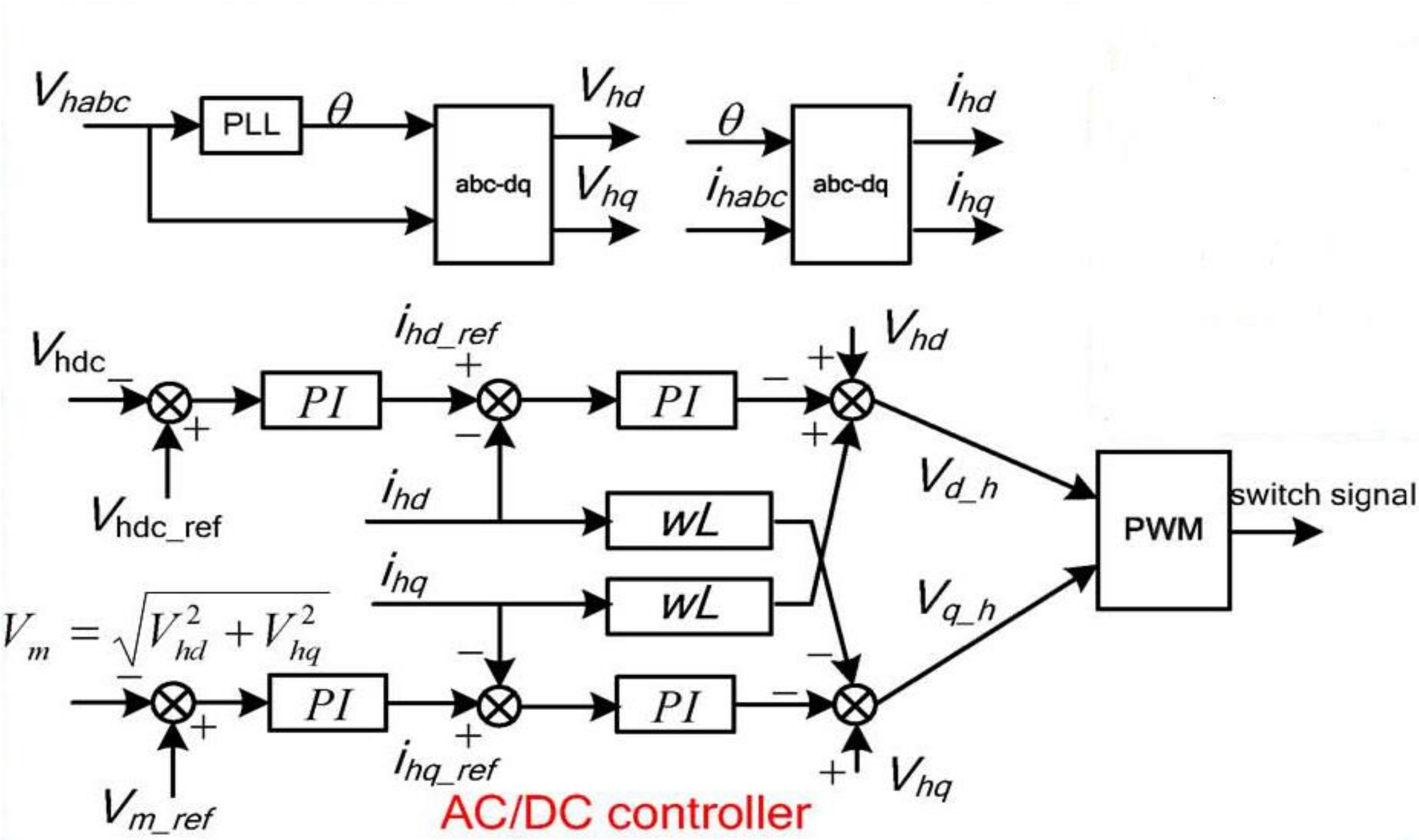
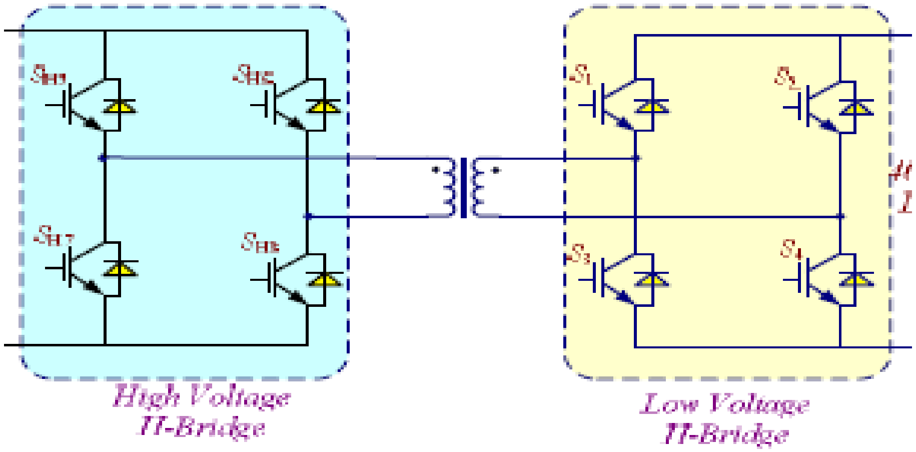


Detailed Controller logic with Voltage and Current Control Loop

Modeling of DC/DC Stage of SST

- The dual active bridge consists of a high voltage H-Bridge, a high frequency transformer and a low voltage H-bridge. The rectifier controls the high voltage DC link voltage and the input current to be sinusoidal from the AC input.



Dual Active Bridge

- The rectifier controls the high voltage side DC link voltage and the input AC current to be sinusoidal. The low voltage DC link is regulated by the DAB converter.

Cont…

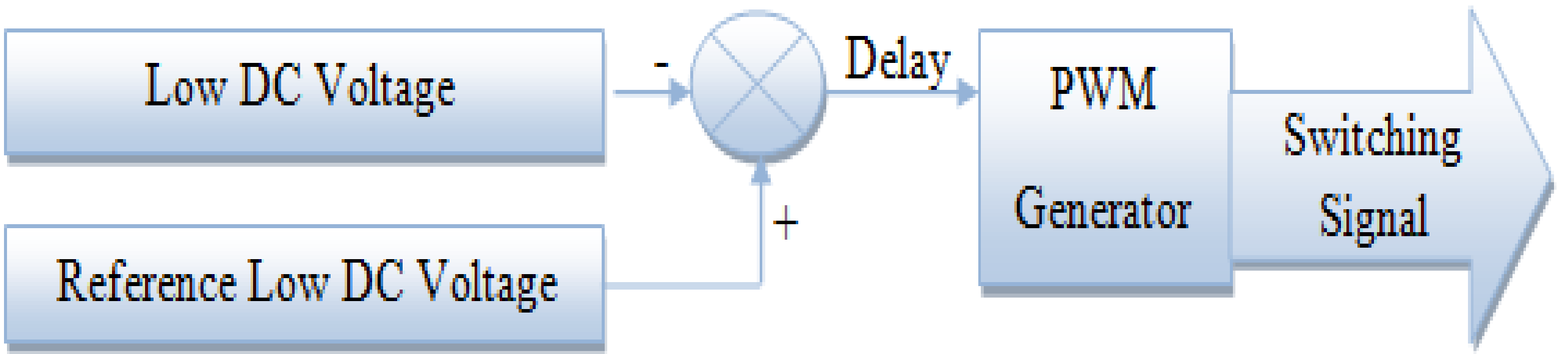
- The dual active bridge topology offers zero voltage switching for all the switches, relatively low voltage stress for the switches, low passive component ratings and complete symmetry of configuration that allows seamless control for bidirectional power flow.
- Real power flows from the bridge with leading phase angle to the bridge with lagging phase angle, the amount of power transferred being controlled by the phase angle difference and the magnitudes of the dc voltages at the two ends as given by equation.

$$P_o = \frac{V_{dc} V_{dc_{link}}}{2 L f_H} d_{dc}(1 - d_{dc})$$

where,

V_{dc} is input side high voltage DC voltage, f_H is switching frequency, L is leakage inductance, V_{dc_link} is output side low voltage DC link voltage referred to input side and d_{dc} is ratio of time delay between the two bridges to one half of switching period.

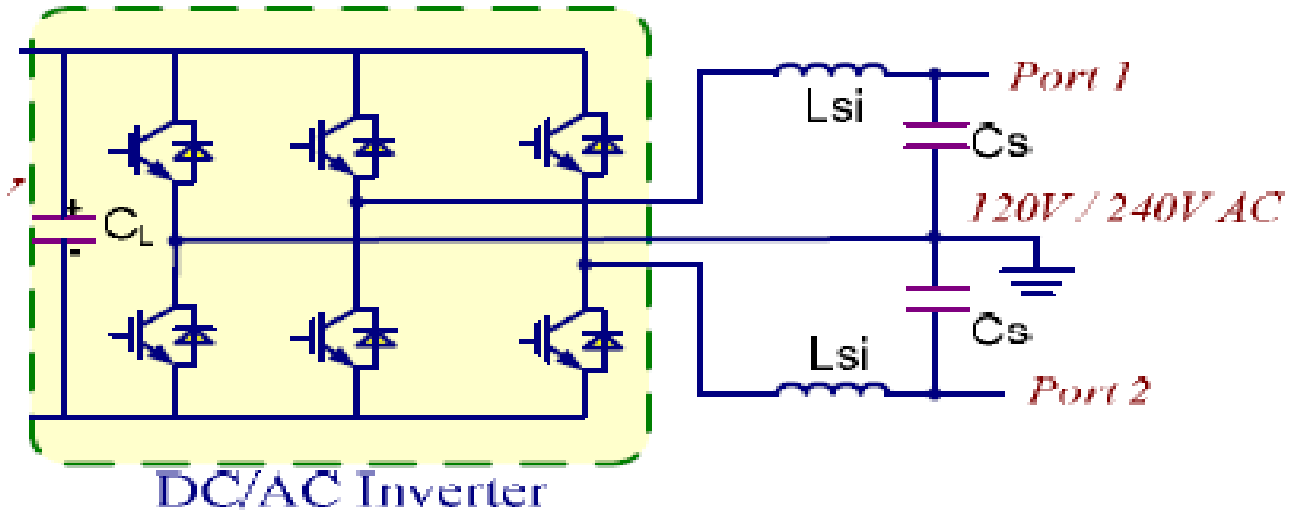
Control Technique for DC/DC Stage of SST



Representation of DC/DC Converter Stage Controller

Modeling of DC/AC Stage of SST

- The DC/AC inverter converts the fixed low dc voltage to fixed AC (Magnitude & Frequency) as per the requirement . The inverter consists of six switches with three phase legs.



Inverter stage of SST

Control Technique for DC/AC Stage of SST

- The inverter stage is controlled using a dual loop strategy in d–q coordinate. The inductor current loop is cascaded as the inner loop such that fast dynamic responding can be guaranteed.
- The controller for converter at the low voltage side can be modified correspondingly when connected with different renewable sources and the integrated functions can still be maintained.
- Due to the bidirectional power transfer characteristics of the system, this controller can also transfer the power from the low voltage side to the high voltage side.

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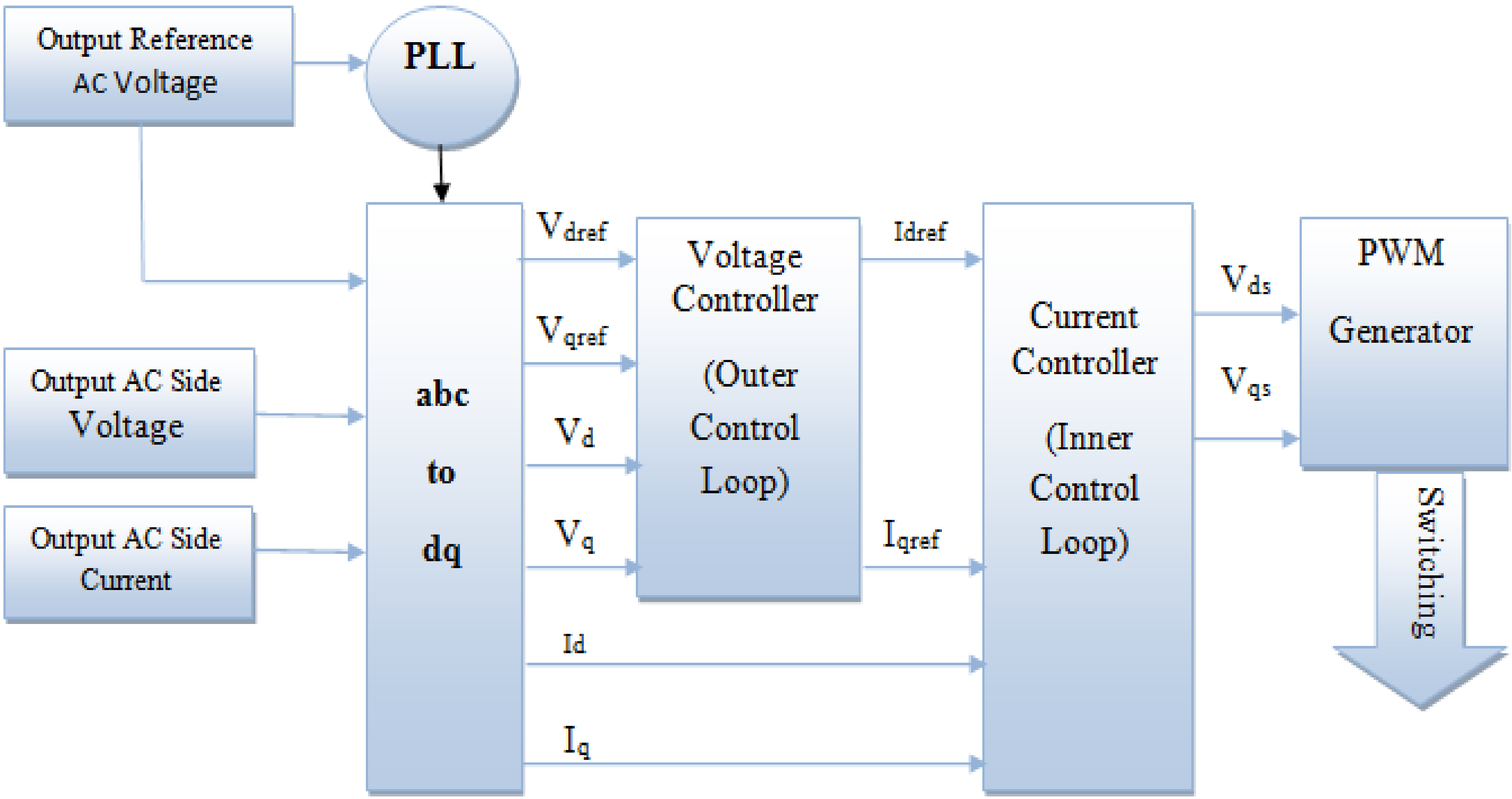

Representation of DC/AC Converter Stage Controller

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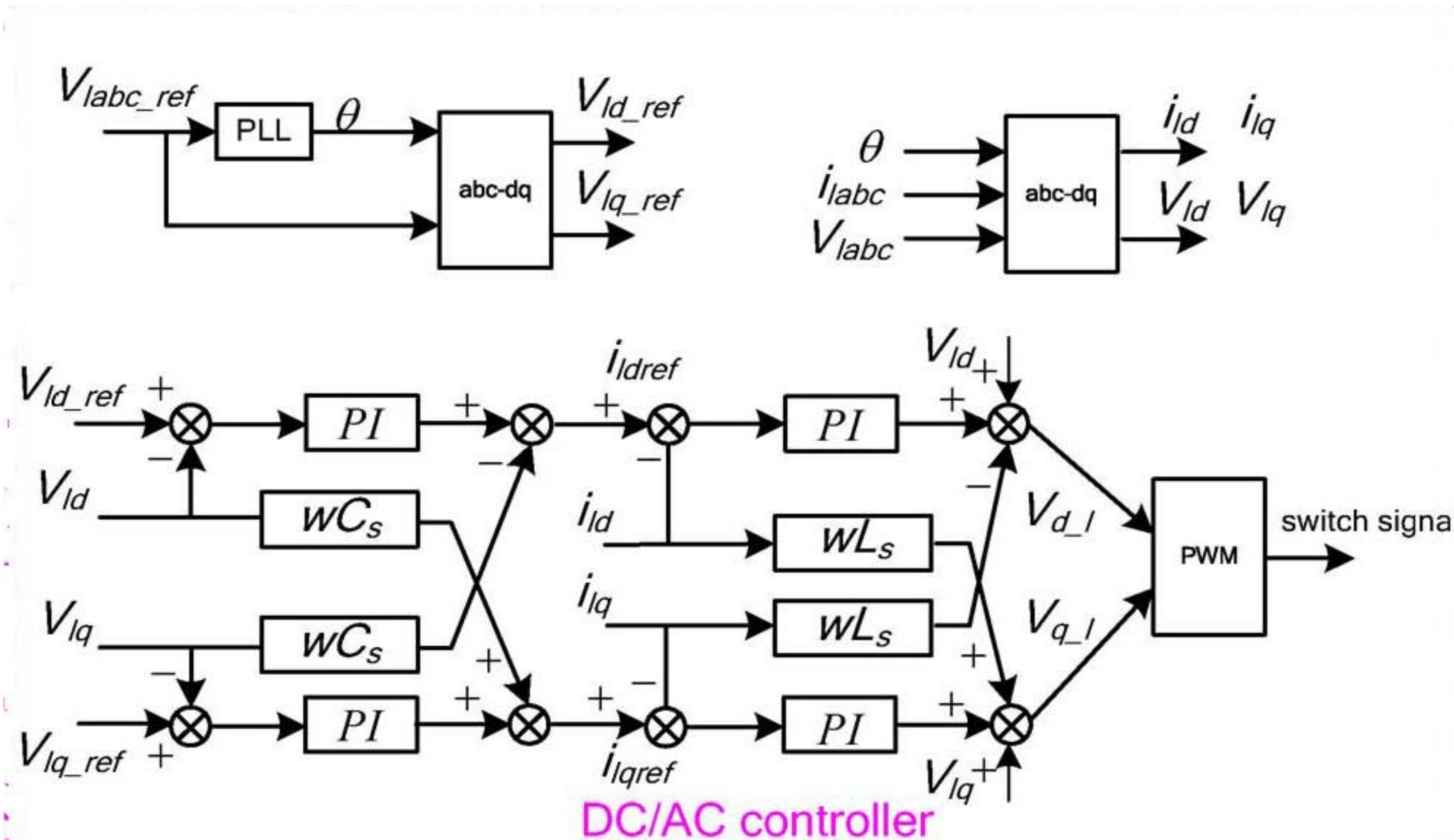
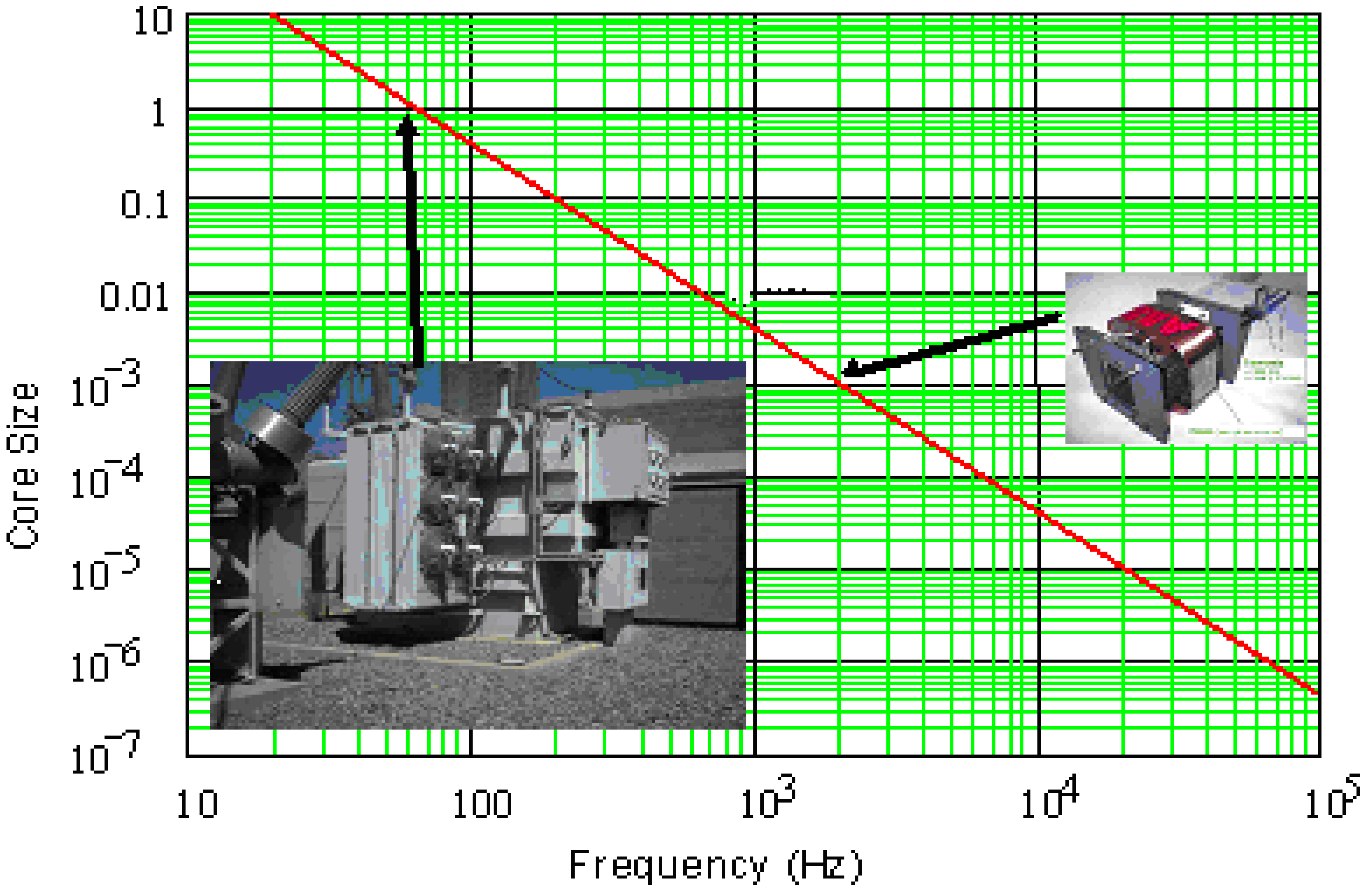


Detailed Controller logic with Inner and Outer Control Loop

4. Functionalities of SST

- Size and Weight Reduction
- Reactive Power Compensation
- Active and Reactive Power Control
- Fault Isolation
- Black Start Capability

Size and Weight Reduction



Transformer core size and frequency relationship

Voltage Sag Mitigation

- One of the most important features of the SST is the voltage sag or swell ride through capability.
- The voltage sag or swell can be compensated by the rectifier stage and will not affect the load side voltage. The maximum input current determines how much a voltage sag the SST can compensate, and the maximum input voltage determines how much a voltage swell the SST can support.
- Furthermore, when the voltage sag is so large that the SST cannot continuously sustain the compensation, the DC bus capacitance (or energy storage) will determine how many cycles the SST can compensate before the system shut down.
- The SST design can be flexible enough to accommodate specific requirements.

Reactive Power Compensation

- The SST rectifier stage not only converts the input AC to regulated DC voltages, but also has reactive power compensation capabilities. Depending on the reactive power reference in the SST controller, the SST can generate or absorb the rated reactive power to the power grid. This fast and controllable local reactive power compensation is beneficial to support the system voltage, reduce the transmission line loss and enhance the power system stability.

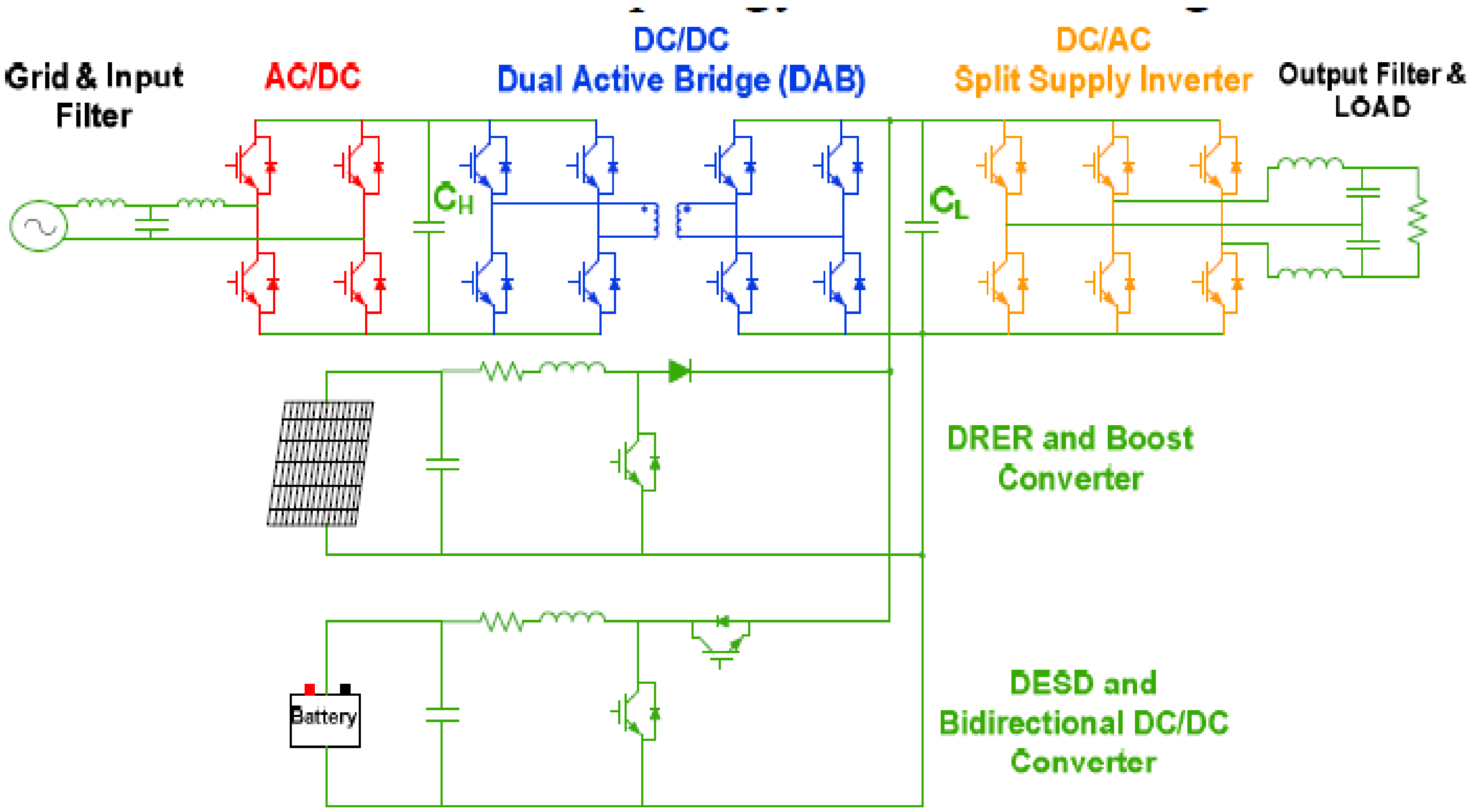
Fault Isolation

- The SST protection scheme for the output short circuit is, the SST will stay online but limit the load current to 2 times of the rated current. Then some of the electronic equipment loads are not affected and still able to operate under a lower voltage. After the circuit breaker (or fuse) trip the fault, the SST will again output rated voltage.

Black Start Capability

- With the interconnection of DRER's and DESD's to the SST, the smart grid is capable of operating in an islanded state.
- The amount of load capable of being restored is dependant on the total amount of DRER and DESD connected to the SST's and must be regulated by the Distributed Grid Intelligence.
- The grid connected and islanded operations of the SST require separate control methods.

Cont…



Solid state transformer with DRER and DESD

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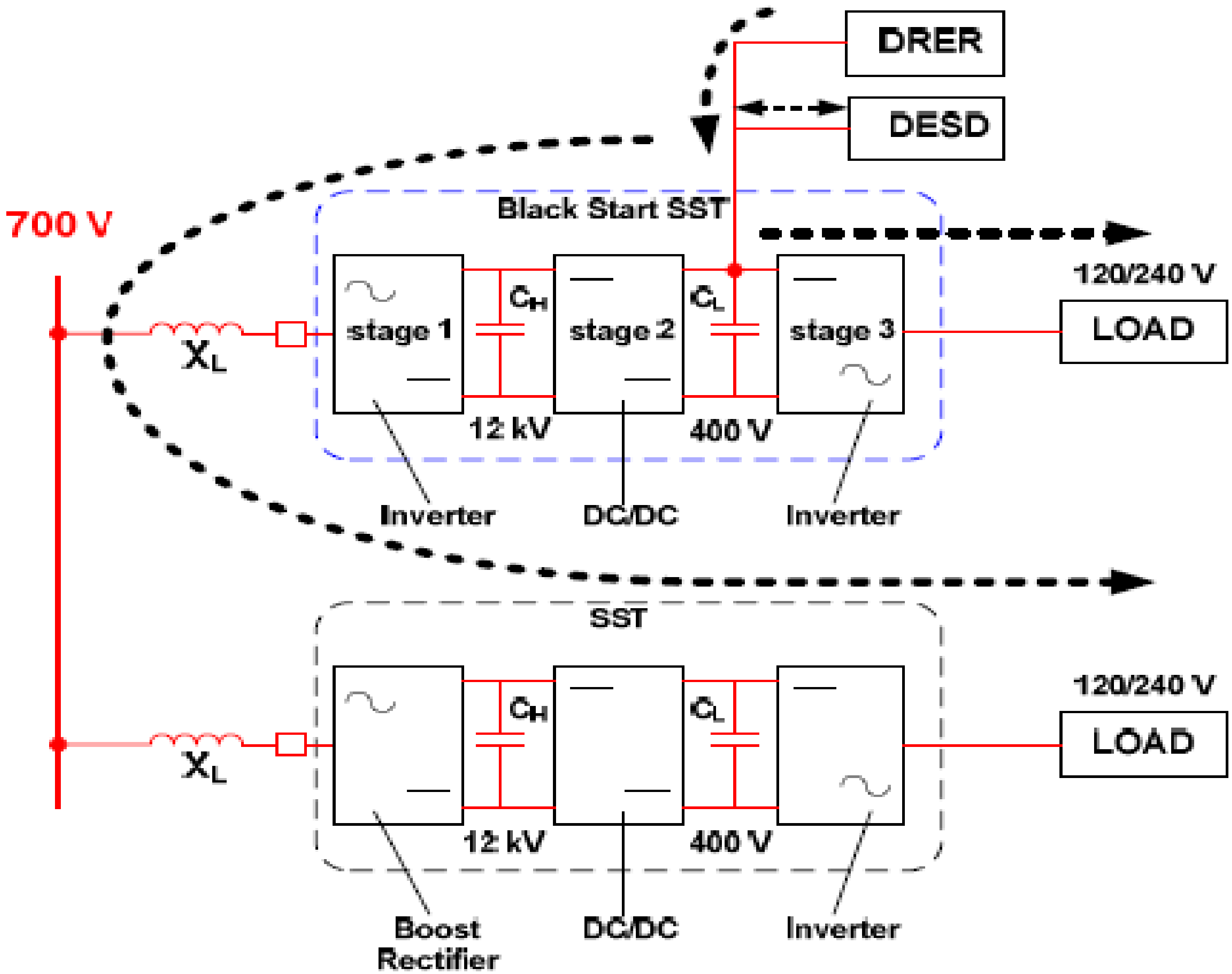
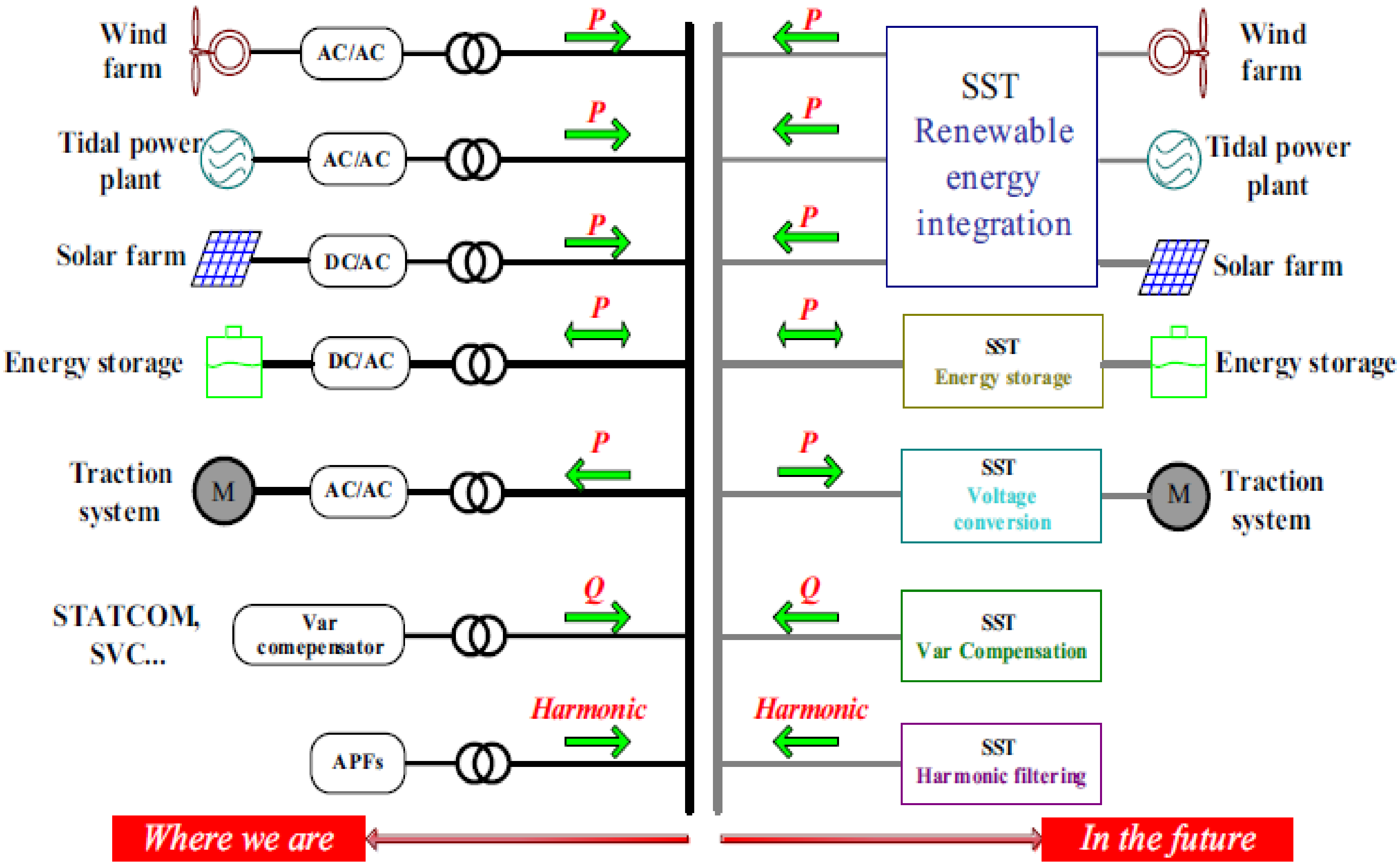


Black start operation of the SST in a microgrid

5. Application Areas of SST

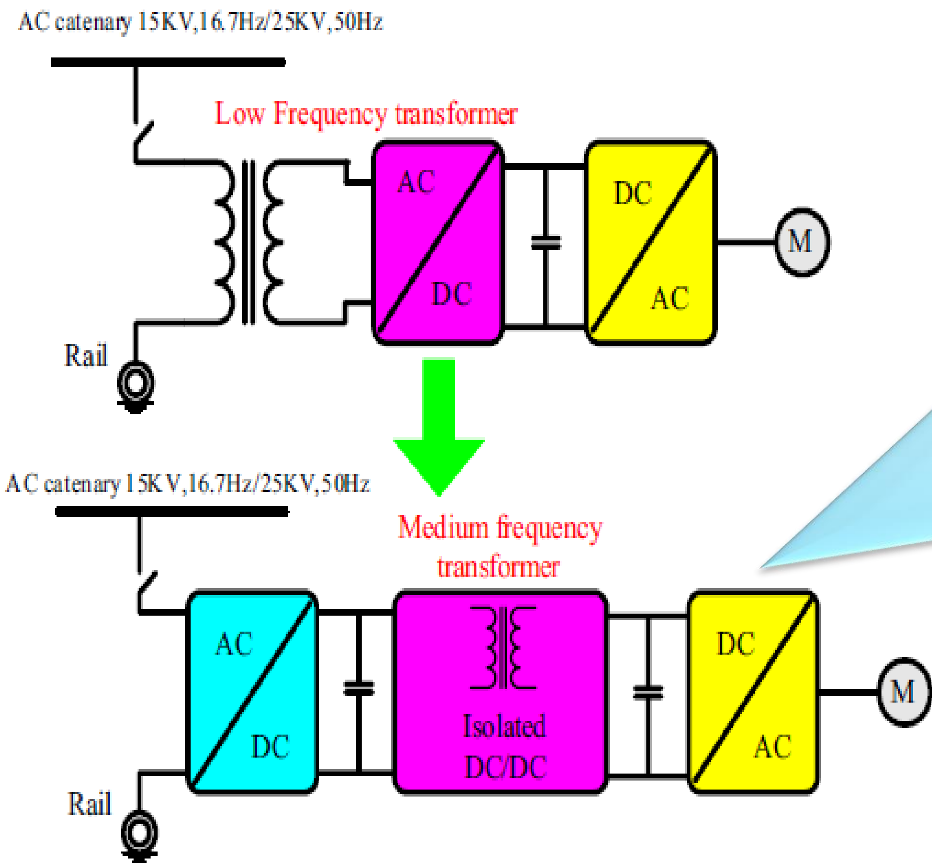
- Overview of Typical Application Areas
- Traction Application
- Wind Power Integration
- DC Charge Station
- UPQC
- Smart Grid Application

Overview of Typical Application Areas



Traction Application

- In 2012 ABB has announced its world's first MW level power electronic traction transformer in the field service.

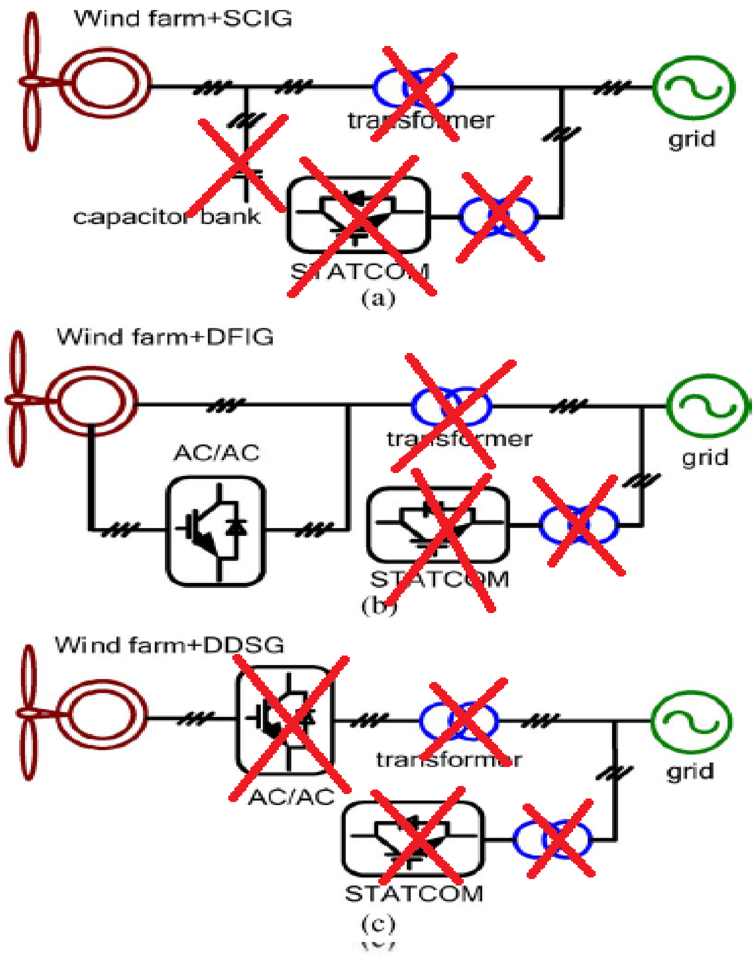


SST in Traction Application

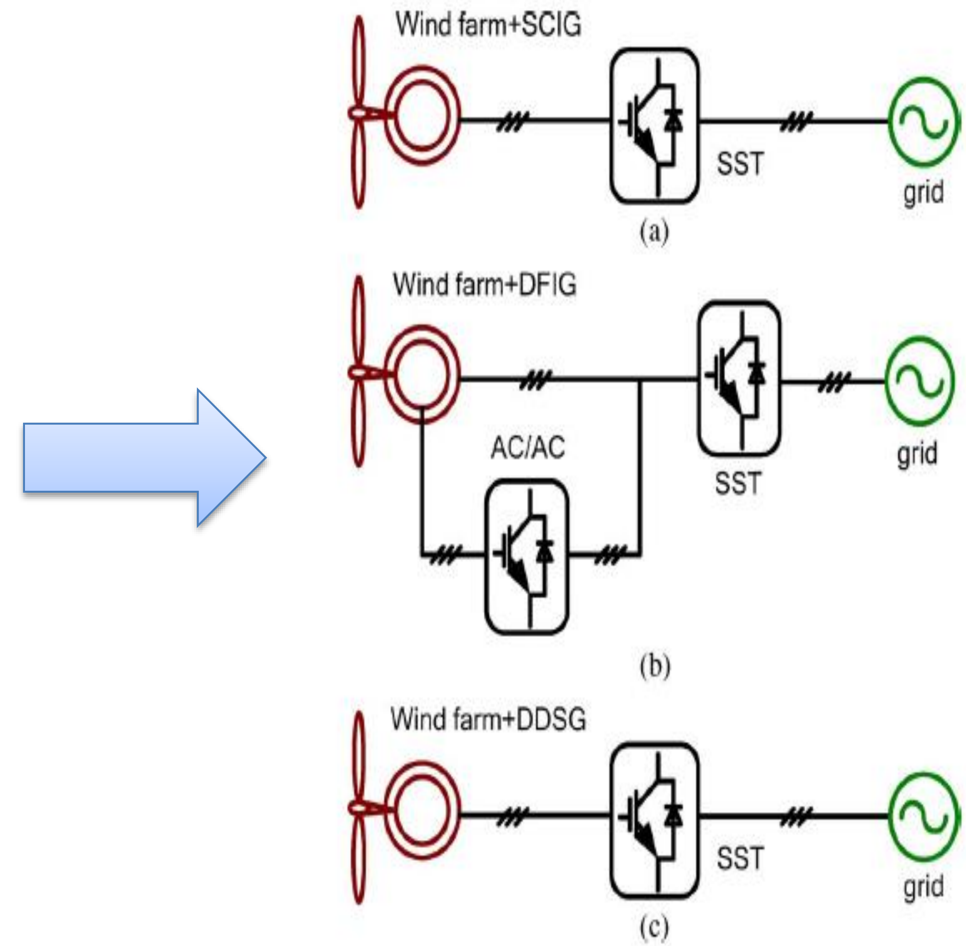
Advantages

- Efficiency Improvement:
  - Conventional: ~88%–92%
  - SST: >95%
- Size and Weight Reduction
- Improved power density

Wind Power Integration



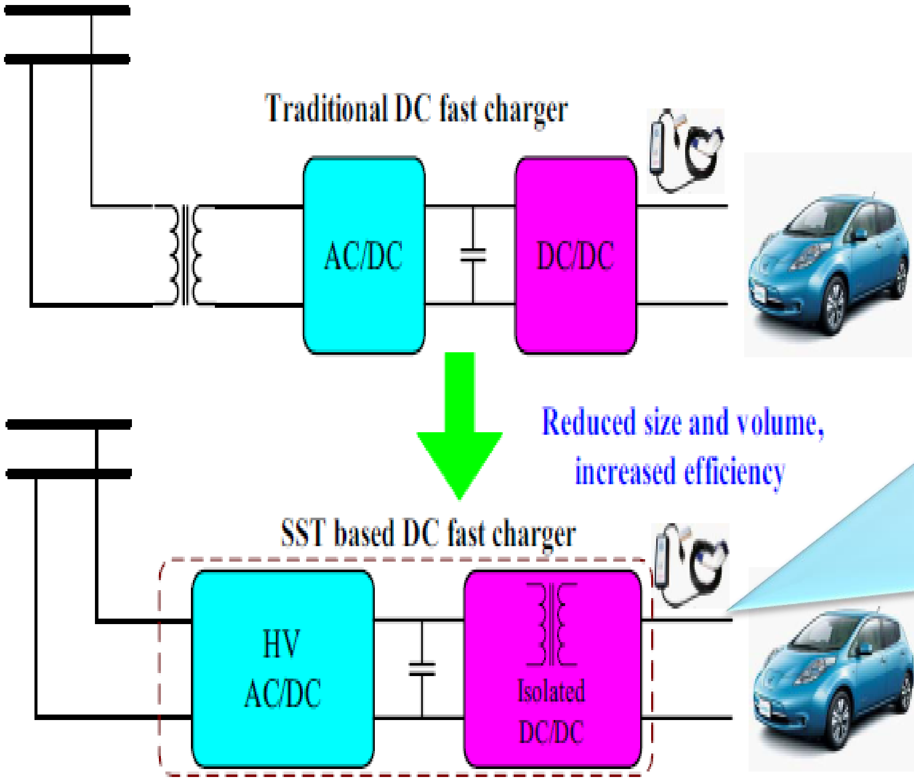
Conventional Wind Power Integration



SST based Wind Power Integration

DC Charge Station

- EPRI has demonstrated a 45-kVA, 2.4-kV fast charging station based on SST technology



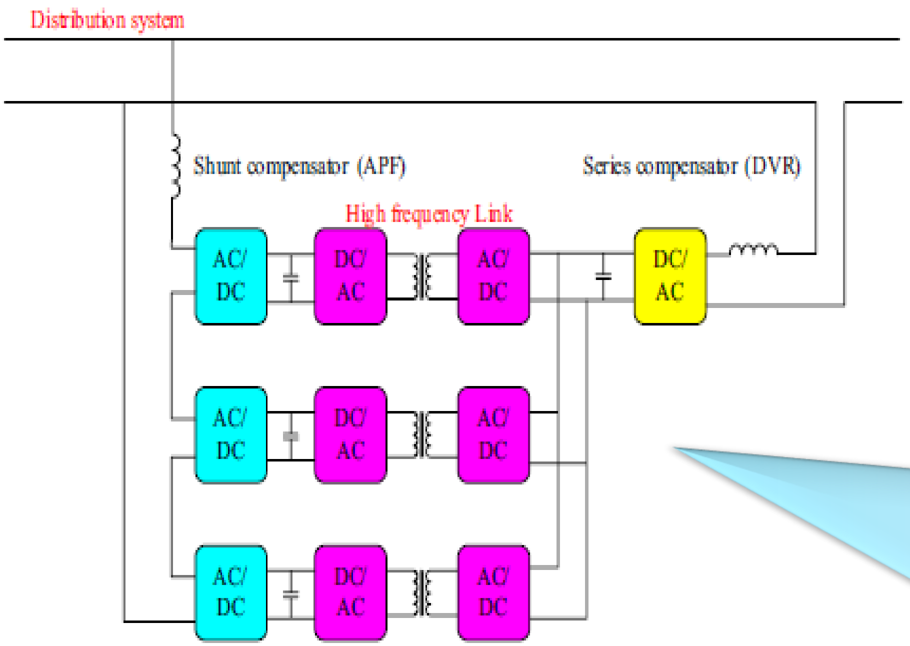
SST Based DC Charge Station

Advantages

- Efficiency Improvement:
  - Conventional: ~90%
  - SST: >95%
- Weight Reduction
- Cost is reduced to half of the conventional technology

SST as UPQC

- Combining the features of working as dynamic voltage restorer and current harmonic filtering, SST can be used as UPQC.



SST as UPQC

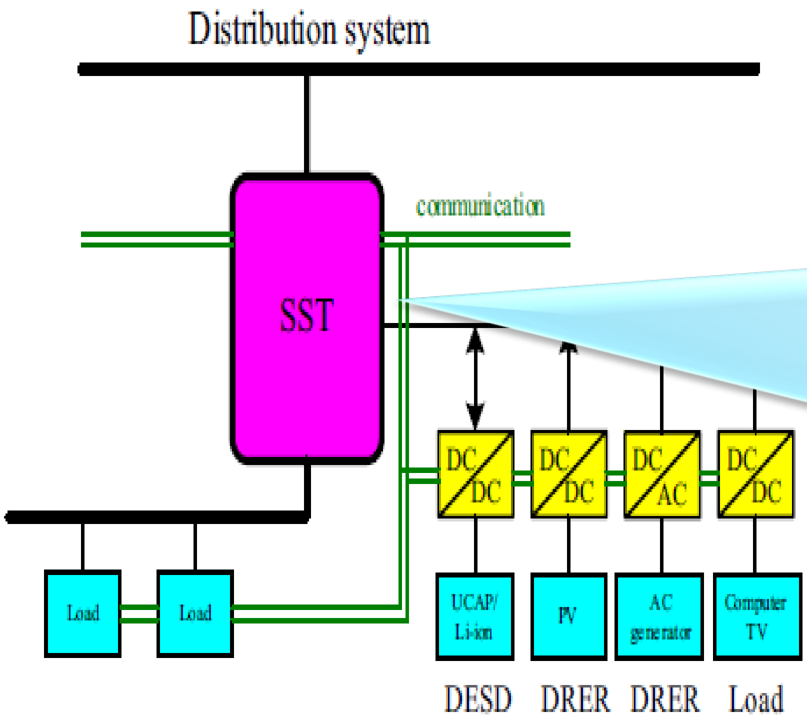
Advantages

•Get rid of both series and shunt transformer.

•Size and Weight can be reduced dramatically

Smart Grid Application

- SST integrated microgrid and it power management strategy was proposed by Xu She in 2011.



SST based Microgrid

Advantages

- LVDC Link helps to integrate DERs and DESDs
- More compact, lighter and more integrated system can be obtained.

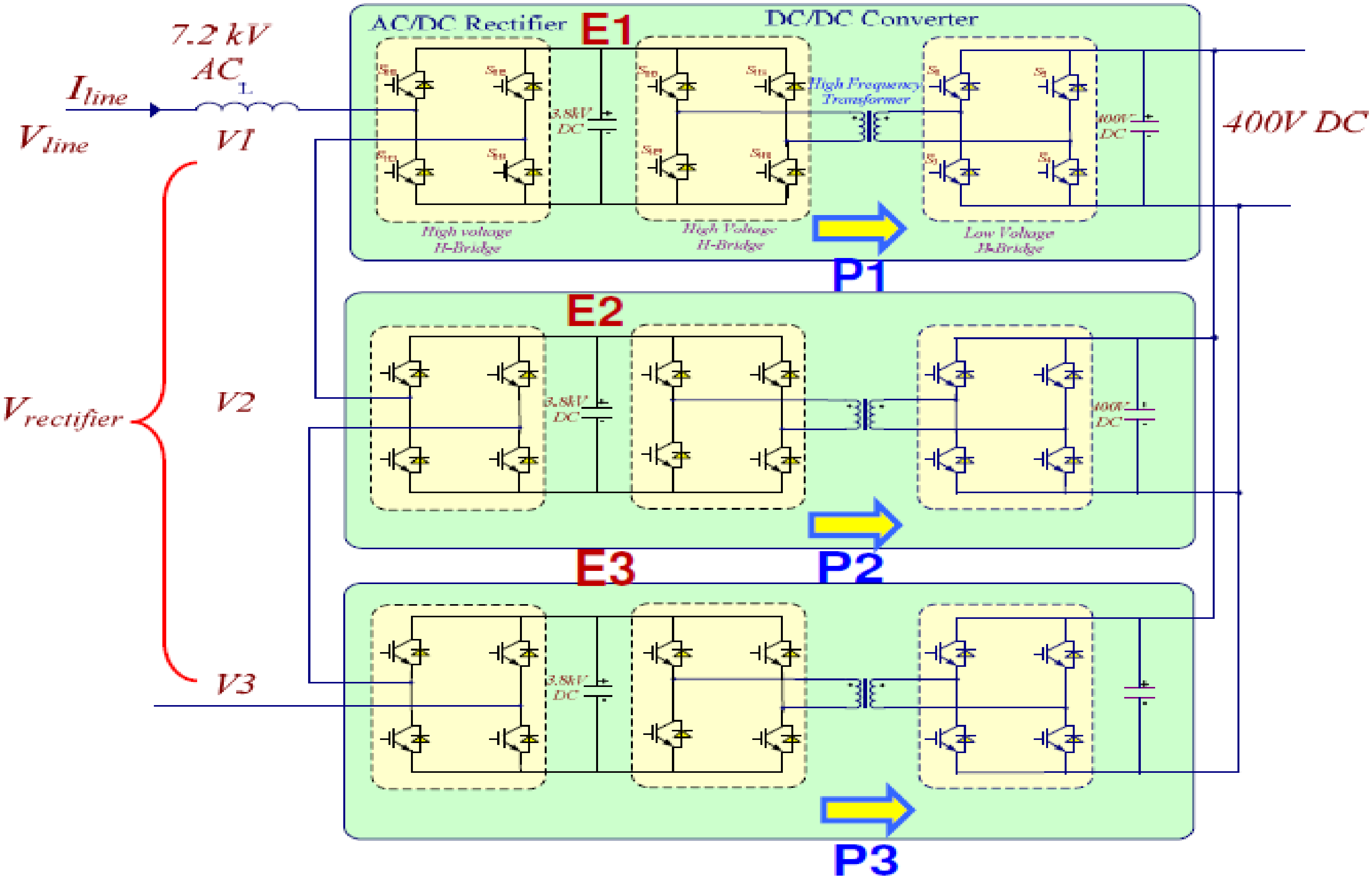
5. Challenges with SST Implementation and Application

- Issues with SST Topology
- Voltage Balance Issues
- Power Balance Issues
- Protection Issues

Issues with SST Topology

- One of the main disadvantages of the cascaded H-bridge converter is the voltage unbalance that could appear on the DC side of different H-bridges (E1, E2, and E3) due to the device loss mismatching and H-Bridge real power differences.
- The unbalance issue becomes worse when the SST operates at no-load or light-load condition, because a small power difference is a significant percentage of the real power and will result in a large voltage unbalance.
- The unbalanced voltage will cause the capacitor or device over-voltage in the H-Bridge and trigger the system over-voltage protection.
- The DAB stage consists of three DAB modules in parallel. The power unbalance (P1, P2 and P3) can be caused by the transformer parameter mismatching (such as leakage inductance or turns ratio) and DC bus voltage differences.
- The power unbalance may cause device over-current issue.

Cont…



Voltage and power unbalance in SST

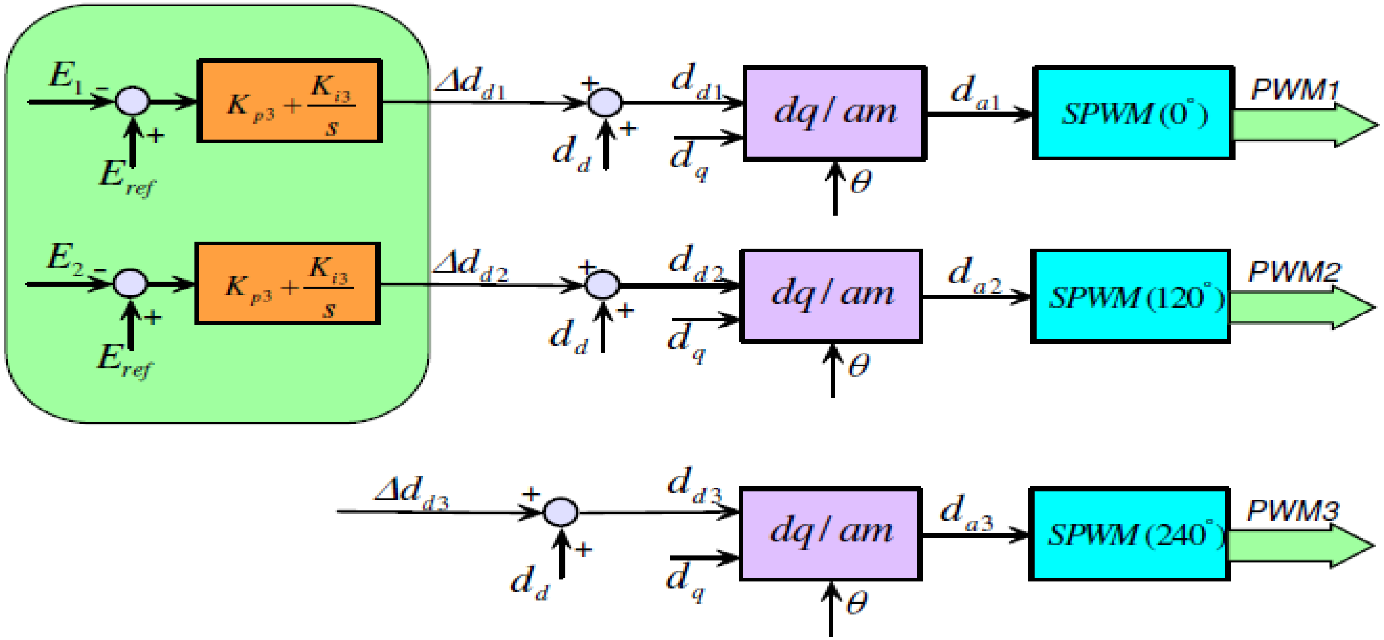
Review of Some Voltage & Power Balance Control Techniques

- In 2009, Y. Liu et al. presented several cascaded H-bridge multilevel converter applications. The low frequency PWM modulation techniques for STATCOM were presented.
  - **Advantage:** The DC bus voltage was balanced by using different switching patterns to charge and discharge each H-Bridge capacitor
  - **Limitation:** The reactive power was not controlled
- In 2008 , J. A. Barrena et al. presented an individual voltage balancing strategy to balance the DC bus voltage with PWM modulation.
  - **Advantage:** The method maintains the delivered reactive power equally distributed among all H-Bridges.
  - **Limitation:** However, the method is based on the STATCOM application and no power unbalance constraints are mentioned in the paper.

Cont…

- In 2008, H. Iman-Eini et al. presented a method that ensures the DC bus voltages converge to the reference value when the loads have different power.
  - **Limitation:** The method results in different switching frequencies for the H-Bridges and a complicated controller implementation.
- J. I. Leon et al. presented different PWM modulation methods to balance the DC bus voltages.
  - **Limitation:** The balance range and power control are not included

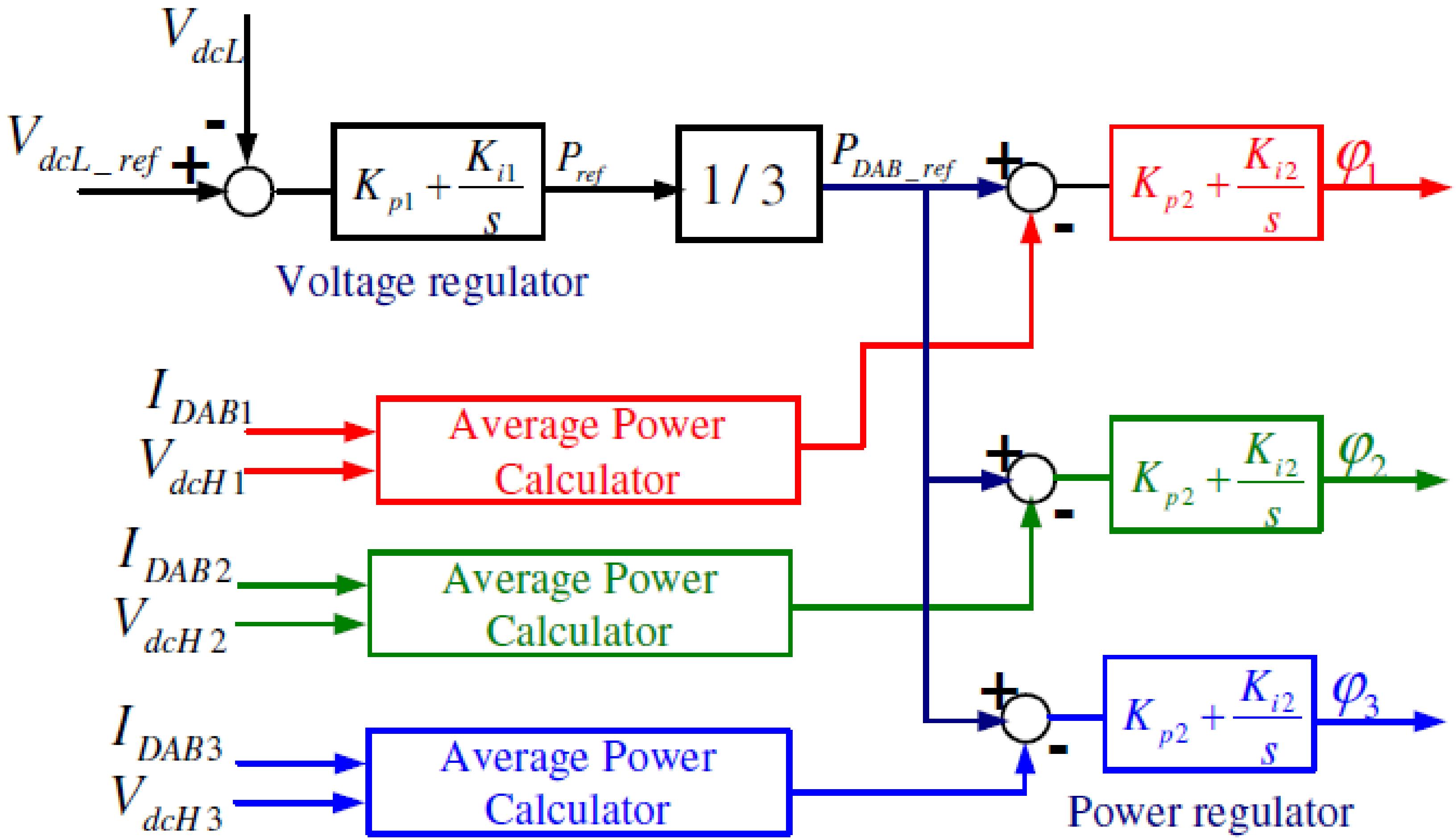
Voltage balance Controller based on Single Phase d-q Vector Control



Voltage balance control based on single phase d-q vector

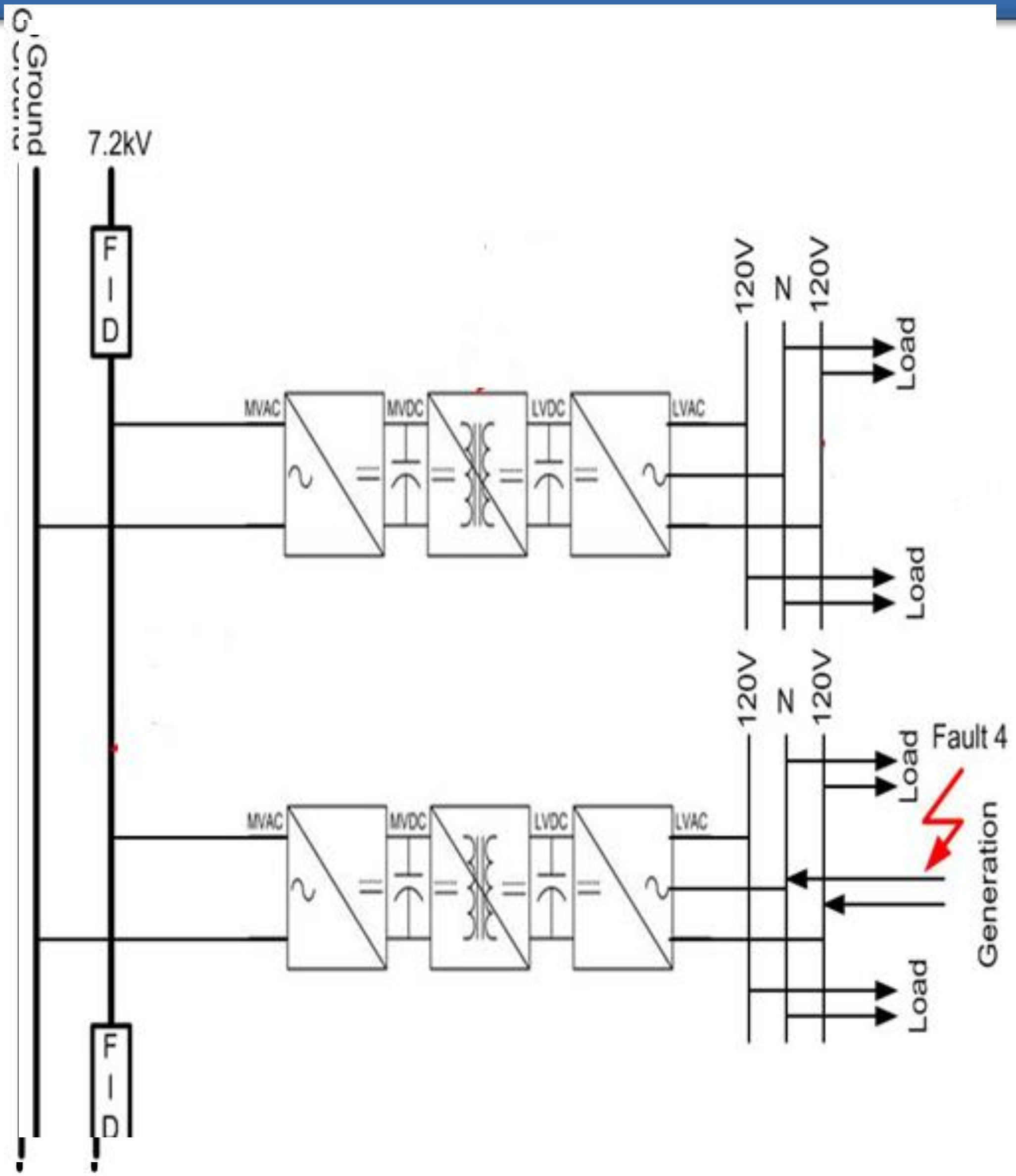
- Due to the intrinsic constraints of the cascaded H-Bridge circuit, in order to maintain the DC bus balanced, the real power unbalance range of the H-Bridges is limited. This limitation is determined by the input AC voltage, DC bus voltage reference and the input inductance.

Power balance Control Technique



Power balance controller

Fault Locations in SST Interfaced Systems



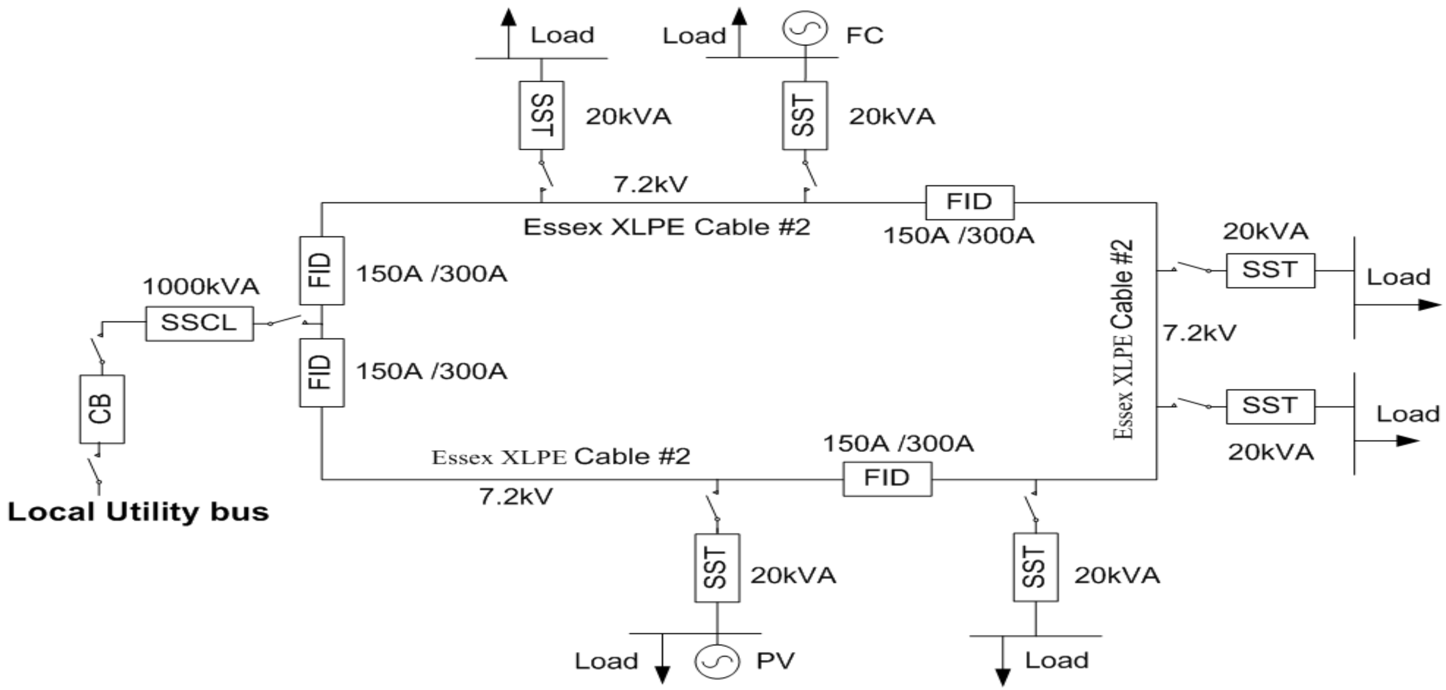
Different Fault Locations in SST based DG system

- Line fault: Short circuit to ground in the 15kV (7.2kV) cable/line.
- SST fault: Component failure in the solid state transformer.
- Distribution system fault: Short circuit in the loads.
- Local generation fault: Fault in electronics, solar panel, micro-turbine or fuel cell.

Protection Issues with SST Interfaced Systems

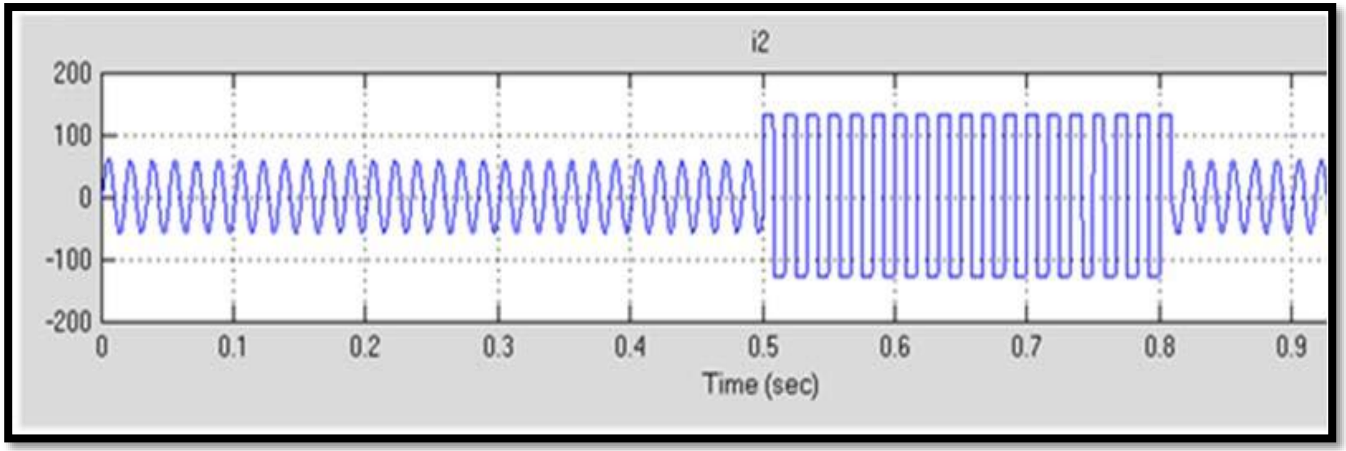
- Overcurrent relay operation hindered because of limited fault current (1.5 to 2 pu) through power converters of SST
- Symmetrical component analysis failed due to unsymmetrical nature of the system with DERs and DESDs.
- The conventional differential protection is not appropriate for a distribution such as the FREEDM system as well because the protection range of the system is the section, including not only the distribution lines, but the loads.

Cont…



- A computer model using the Matlab/Simulink program has been developed for the FREEDM loop. This model represents the supply network with an impedance of j*4.147 ohm and a source voltage of 7.2 kV. The loop is rated at 1MVA, and the rounded value of the rated current is 1MVA/3*(7.2kV) ~ 50 A. A solid-state current limiter limits the utility-produced short circuit current. Line or cable loop impedance is neglected, thus representing the worst-case scenario.

Cont…



Short Circuit current on a 7.2 kV line

- The above Figure shows a short circuit current on a 7.2 kV line. The current limiter has produced a square shaped current with about 130A amplitude. Without the current limiter, the short circuit current would be more than 1000A.

Different Fault Detection Techniques in SST based Systems

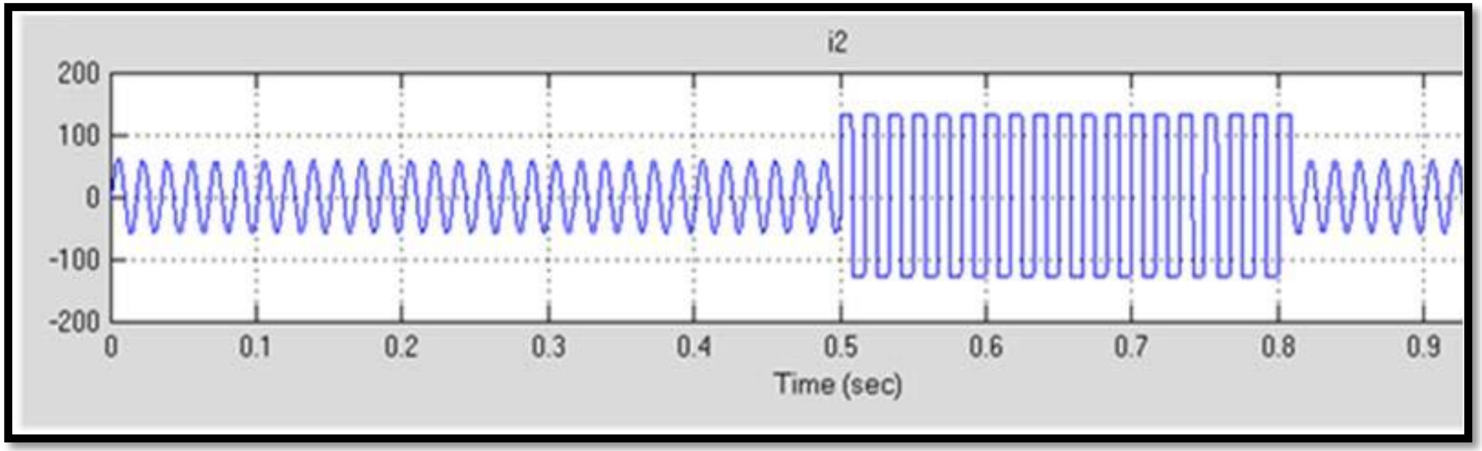
I. Fault Current Wave Shape detection technique.

II. DC bus Undervoltage and Overvoltage Protection technique.

III. Wide Area Differential Protection/ Pilot Protection technique.

IV. Hierarchical Sectional Protection technique.

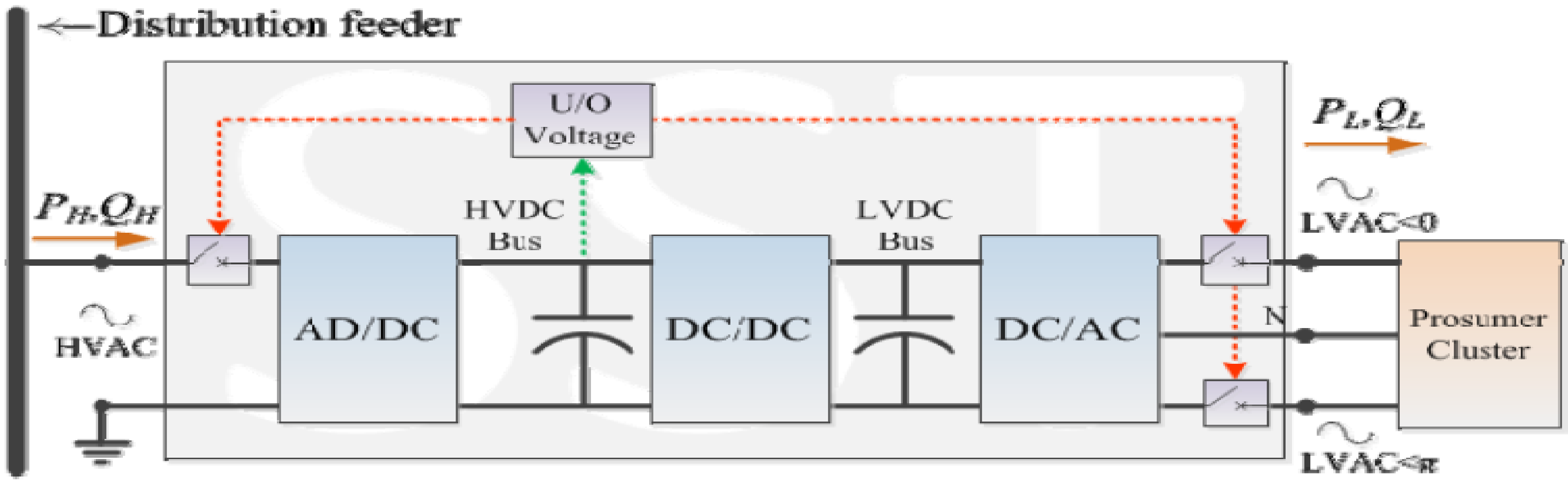
I. Fault Current Wave Shape Detection Technique



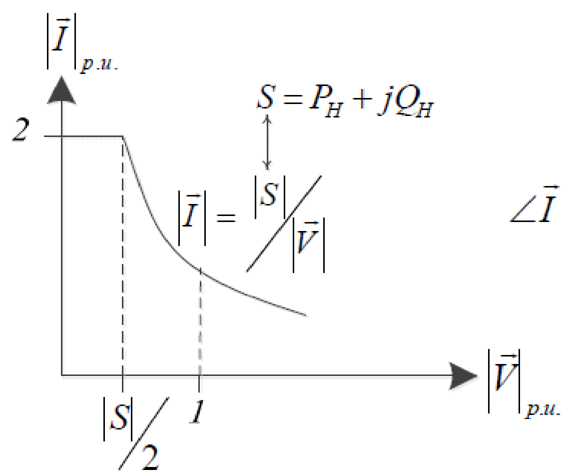
Fault Current Characteristics due to use of Current Limiter within SST converter

- The use of Solid State Current Limiter (SSCL) makes the fault current as square wave shaped (non sinusoidal).
- So by detecting the presence of high value of harmonics for a non sinusoidal/square shaped current wave, fault condition can be detected.
- But the discrimination between overload condition reaching the current limiting value and the fault condition is not possible by this method.

II. DC bus Undervoltage and Overvoltage Protection Technique

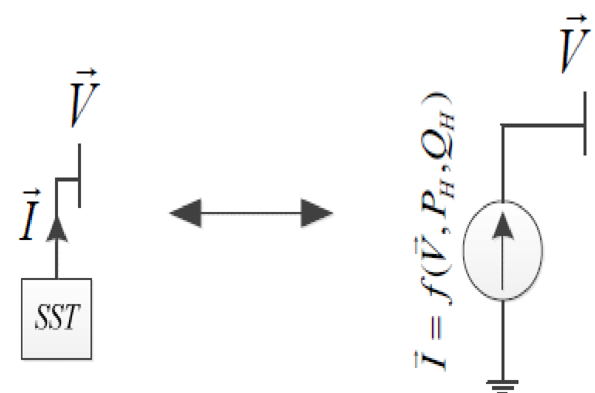


Basic Configuration of SST Connected with Distribution Feeder and Prosumer Cluster



$$\angle\vec{I} = \angle\vec{V} - \tan^{-1}\left(\frac{Q_H}{P_H}\right)$$

V-I Characteristics of SST



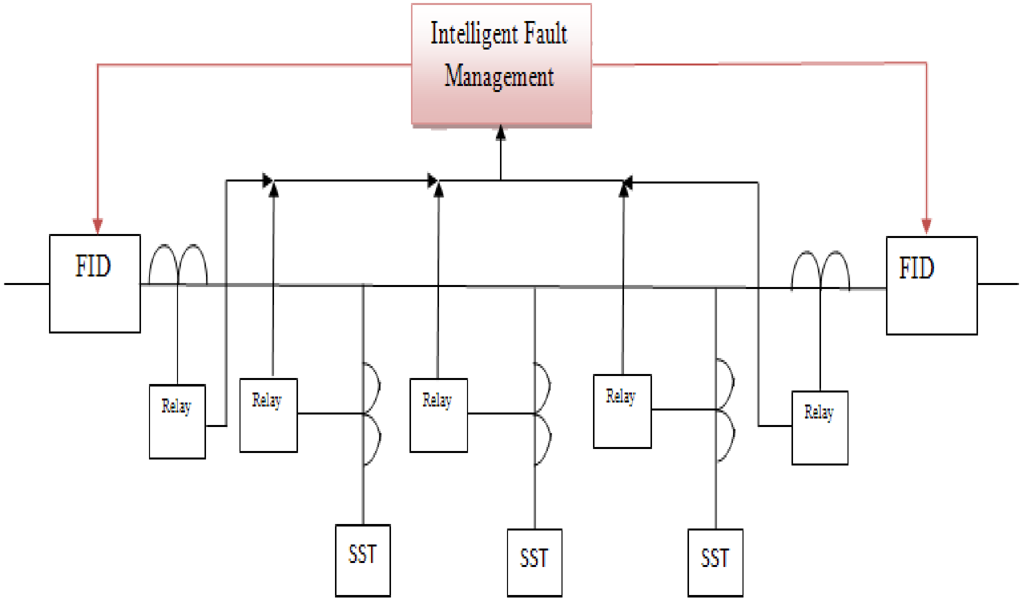
Fault Model of SST

Cont…

❖ SST Protection Scheme:

HVDC Bus Voltage	Trip Time
$V < 0.7pu$	Immediately
$0.7pu \leq V < 1.2pu$	Normal Operation
$1.2pu \leq V$	Immediately

III. Wide Area Differential Protection Technique:

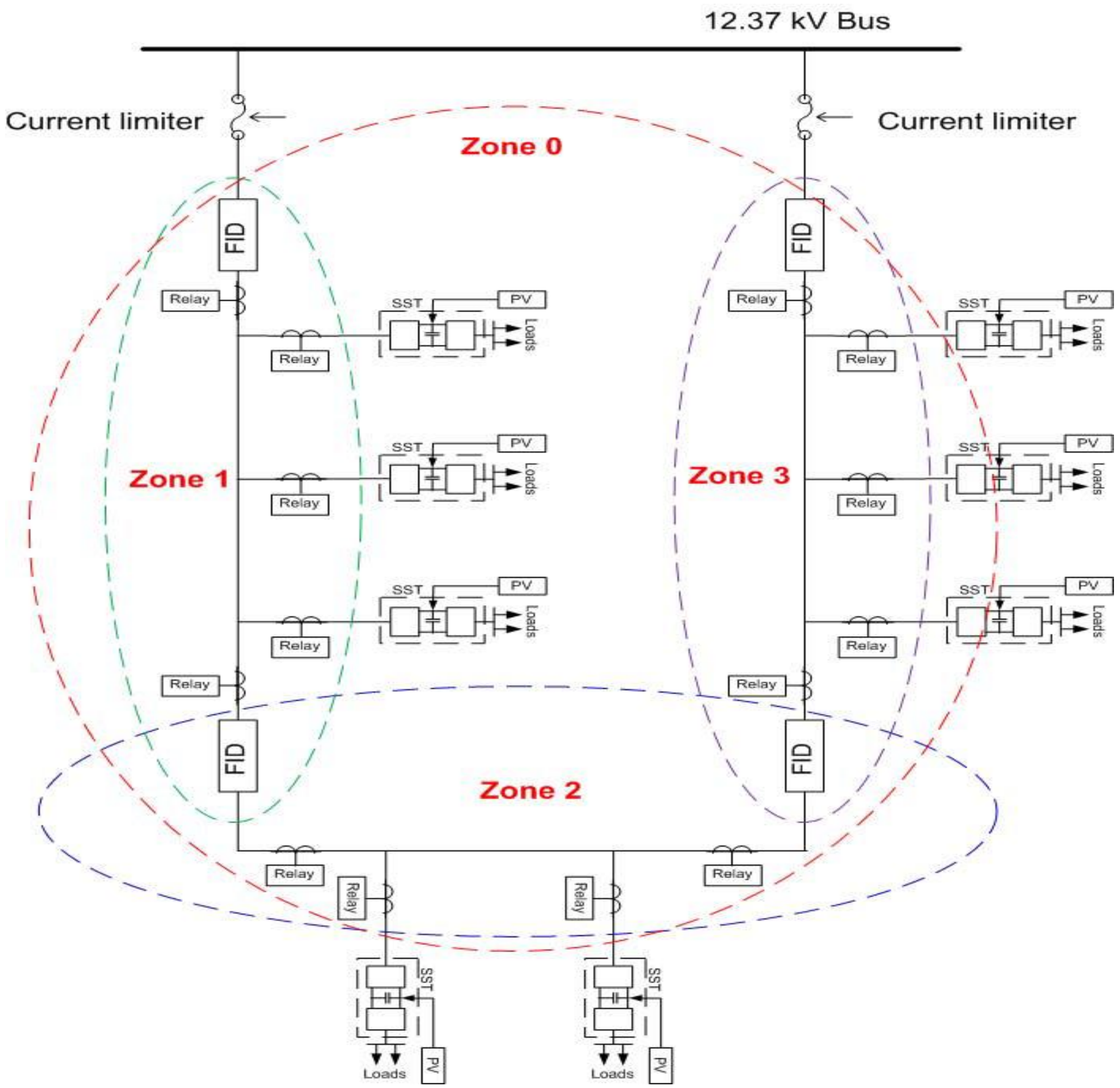


Concepts of Fault Location Detection in a Section

- the sum of the currents is zero in case of an outside fault. In case of an inside fault, the sum of the currents is not zero.
- If the fault occurs within the section, the Intelligent Fault Management computer will activate the FID to clear the fault.
- Typically, the digital relays sample the analog current signal 6 to 12 times in a cycle. They calculate the rms value, initiate circuit breaker operation, and transmit the rms value through the SCADA system to the energy management center. This results in a minimum fault clearing time of 3 cycles.

- The computer-controlled FREEDM loop requires much faster fault clearing because the electronic circuit breaker interrupts the current within few microseconds and without arcing.
- To assure reliable operation, the computer should average a quarter cycle (10-20) samples. The sampling should be more than 250 per cycle.

Cont…



12.37 kV Bus
Current limiter
Current limiter
Zone 0
Zone 1
Zone 2
Zone 3
FID
Relay
SST
PV
Loads

III. Hierarchical Section Protection:

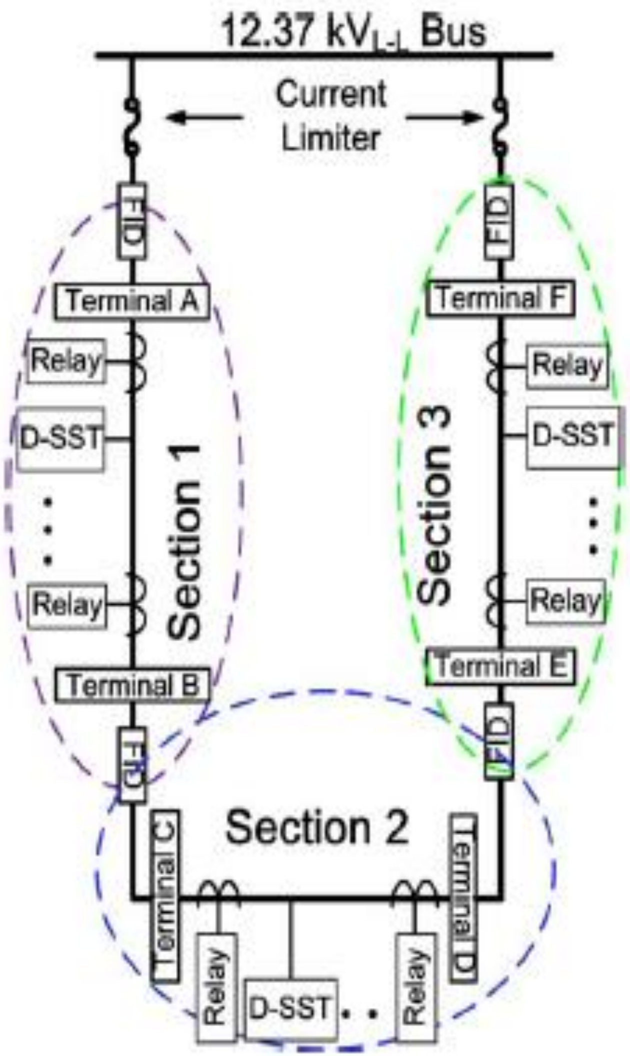
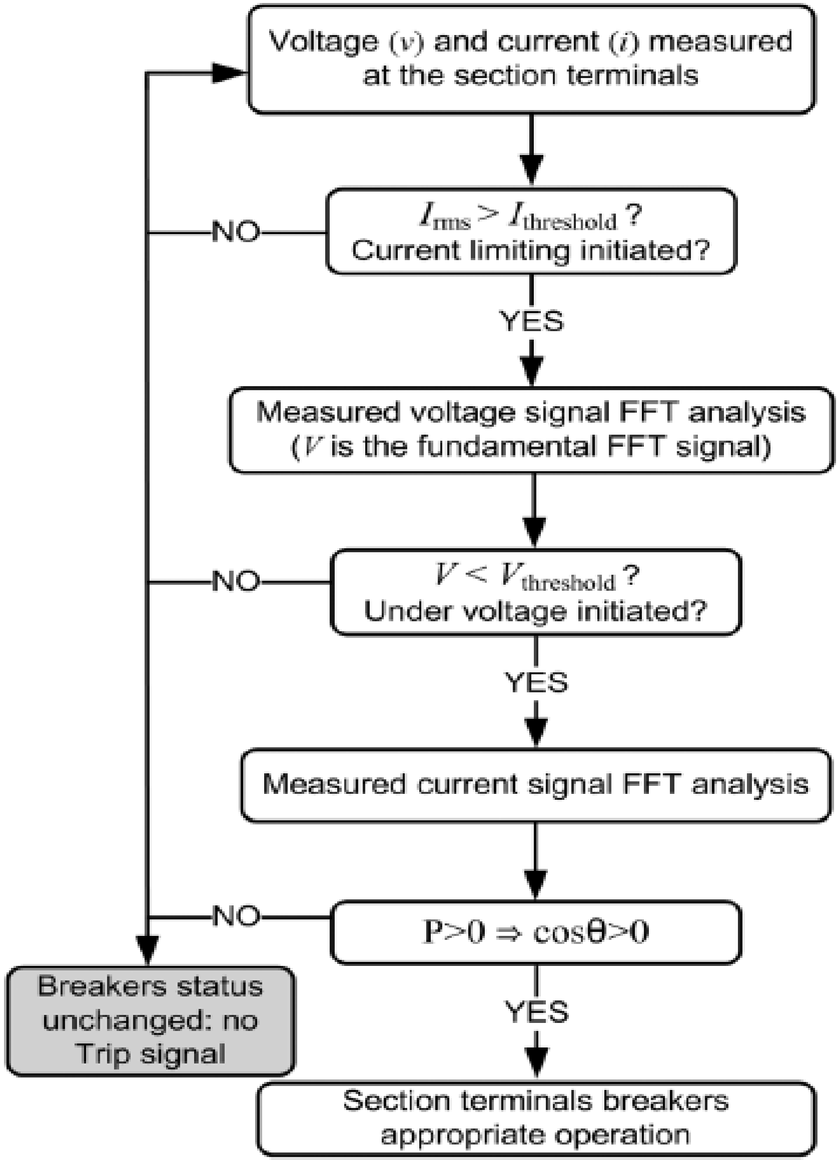
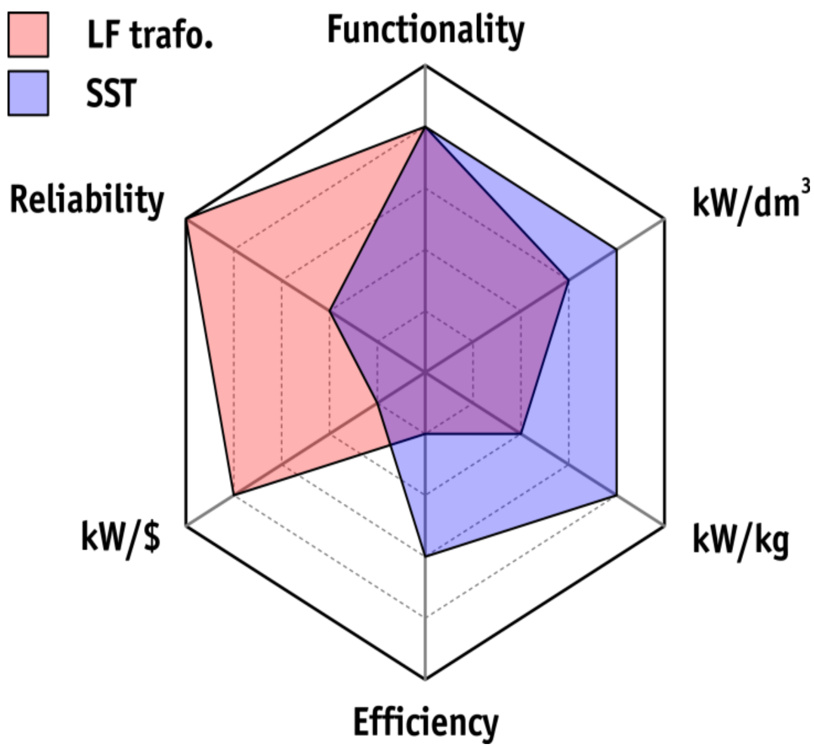


Illustration of system protection with sections

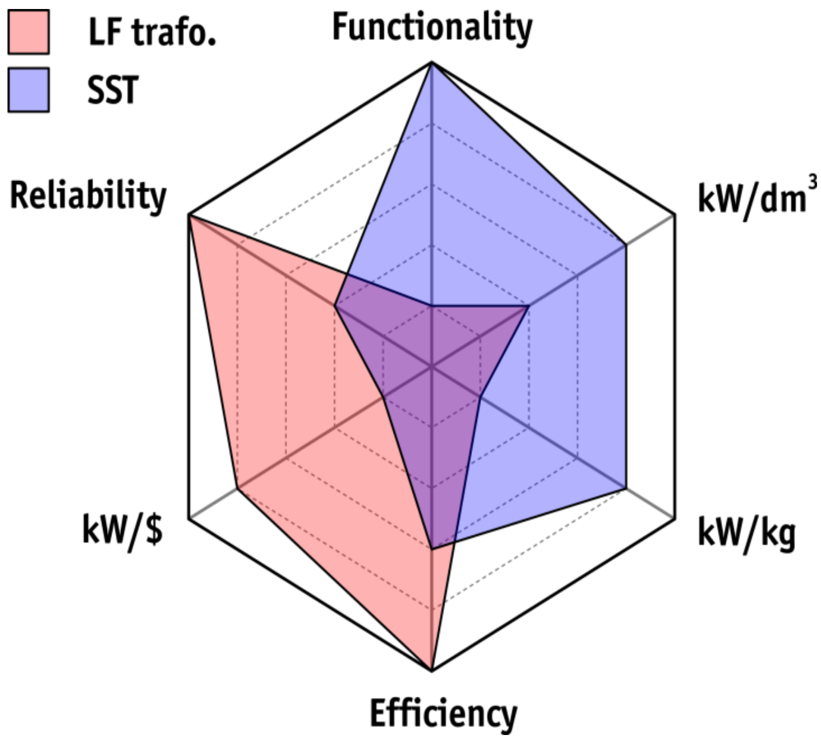


Flowchart for novel fault location algorithm

6. Conclusion



Conventional Traction Transformer and SST



Conventional Distribution Transformer and SST

7. Future Research Directions

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- MF Transformer Construction featuring High Insulation Voltage
- Thermal Management (Air and H2O Cooling, avoiding Oil)
- “Low” Voltage SiC Devices for Efficiency Improvement
- Multi-Level vs. Two-Level Topologies with SiC Switches
- “Optimum” Number of Levels
- Multi-Objective Cost / Volume /Efficiency Optimization (Pareto Surface)
- SST Protection
- SST Reliability
- Hybrid (LF // SST) Solutions
- SST vs. FACTS (Integration vs. Combination of Transformer and Power Electronics)
- System-Oriented Analysis □ Clarify Benefits on System Level (Balancing the Low Eff. Drawback)

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