A Single-Phase Multi-level D-STATCOM Inverter Using Modular Multi-level Converter (MMC) Topology For Renewable Energy Sources

October, 2013

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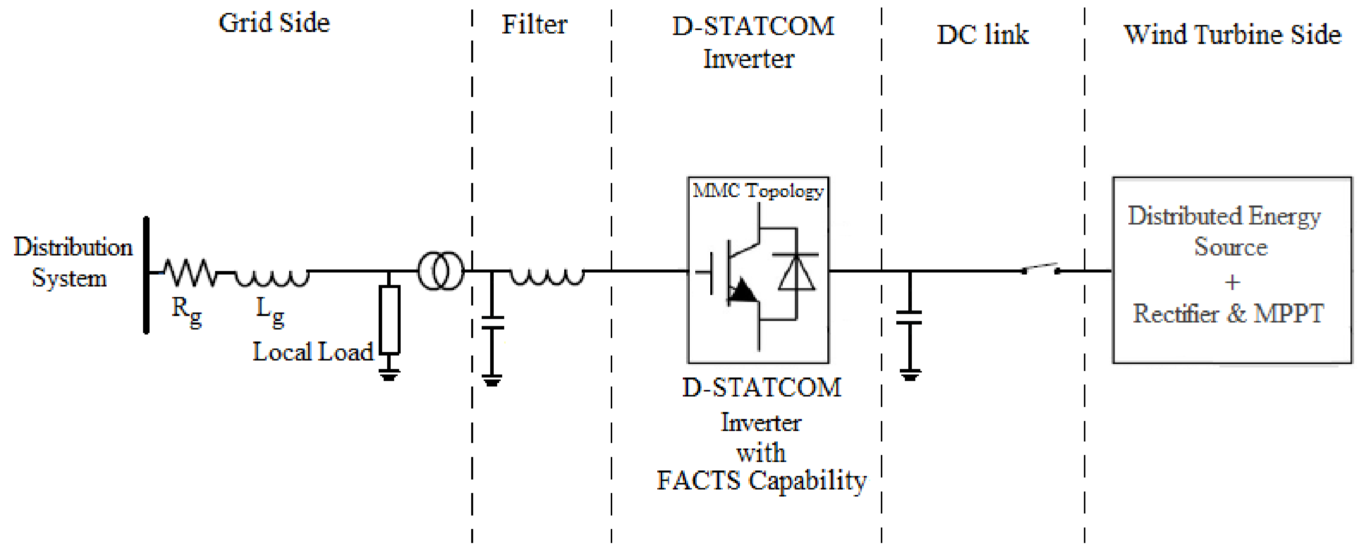
What is D-STATCOM inverter?

- A combination of an inverter and a D-STATCOM in a single unit without additional cost
- Goal: To control the power factor (PF) on feeder lines
- The D-STATCOM option permits the inverter to deliver reactive power fully independent of the wind speed
- Two modes of operation:
  - *When wind speed is too low:*
    - Wind turbine is disconnected from the inverter
    - Inverter acts as a source of reactive power to control PF of the grid (D-STATCOM)
  - *When wind is blowing:*
    - Inverter is able to control active and reactive power (Inverter + D-STATCOM)

Proposed D-STATCOM Inverter Configuration

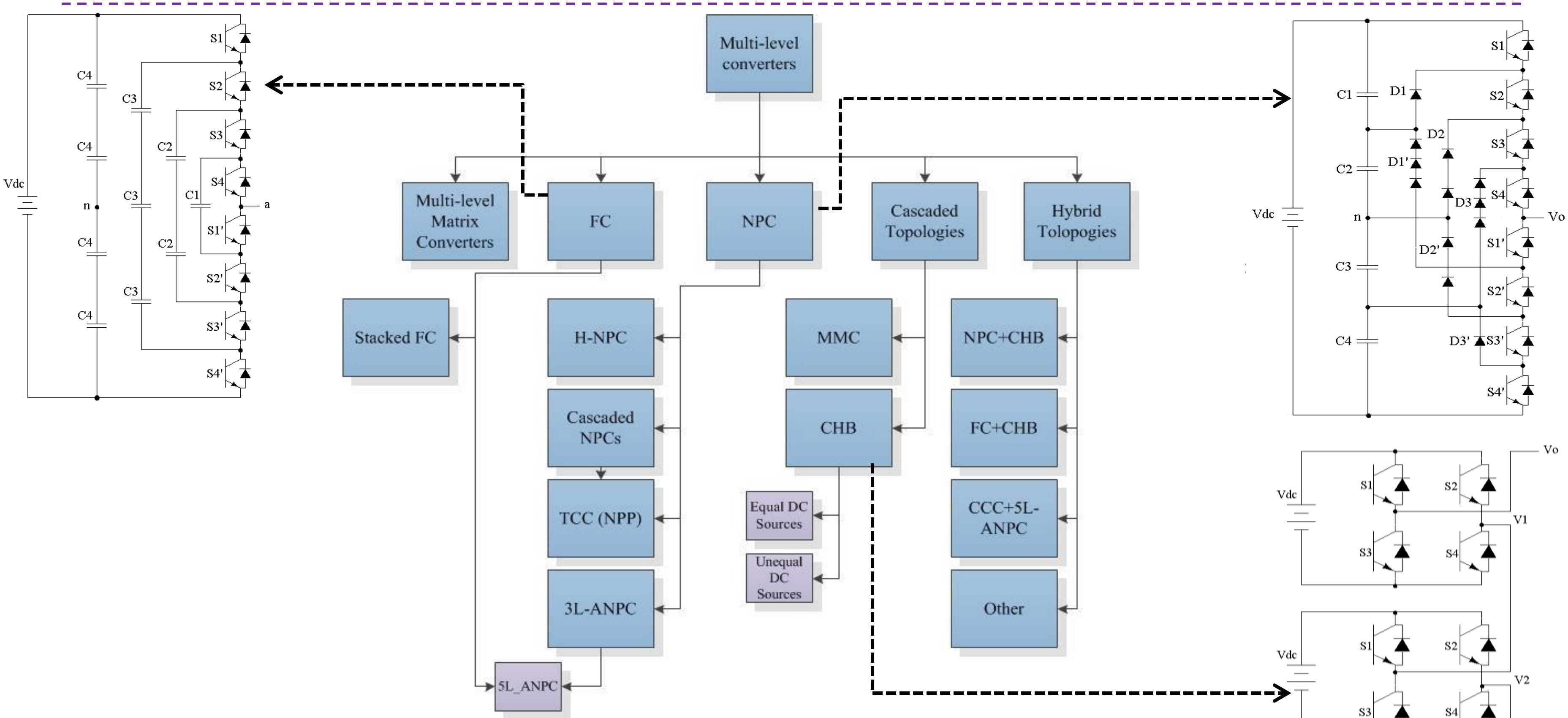


Complete configuration of the proposed inverter with FACTS capability

Multi-level Inverters

- Multi-level Inverter Topologies
  - *History of multi-level inverters goes back to the 1970s*
  - *For medium- to high-power applications:*
    - Large-scale utility applications, electric vehicles, and inverters for renewable energy systems
  - *Lower switching frequency*
  - *Lower THD: Reduces AC filtering*
  - *Less* ${}^{dv}/_{dt}$ *and therefore less voltage stress on the switches*
  - *More components*
  - *Complex control strategy*

Literature Review (Contd…)



Classification of multi-level voltage source converters

Number of Components for 11-level Topologies

11-Level							
Comparison of Components For Different Single-Phase Multi-Level Topologies	Switches	DC Link Capacitors	Clamping Diodes	Auxiliary Capacitors	Inductors	DC Sources	Total
NPC	20	10	90	0	0	1	121
FC	20	10	0	45	0	1	76
CHB	20	0	0	0	0	5	25
HC	38	10	72	9	0	1	130
CHB-Single Source	20	4	0	0	0	1	25
SMC	20	0	0	8	0	2	30
MMC	40	2	0	20	2	1	65

Number of components for 11-level inverter

Modular Multi-level converter (MMC)

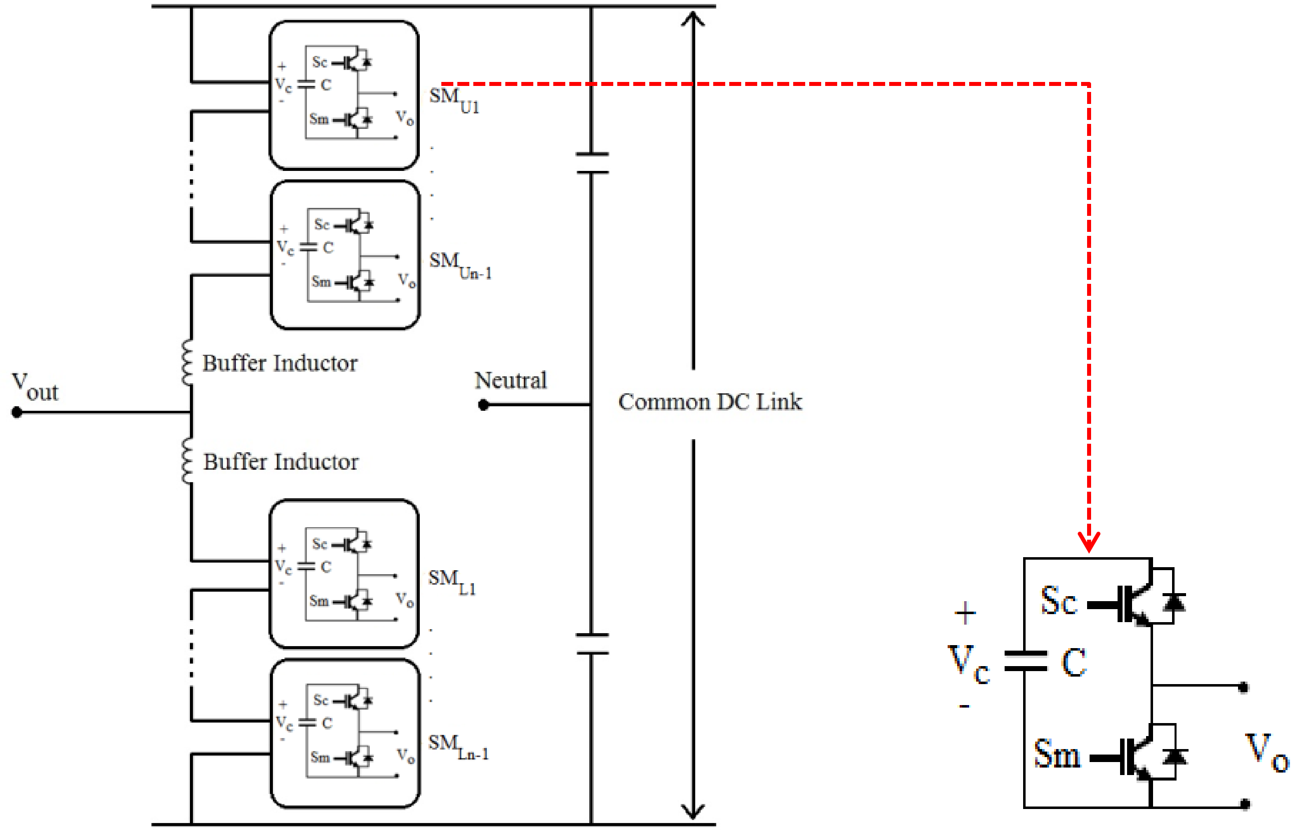
- ***Modular Multi-level Converter (MMC)***
  - Modular topology → Scalable to any level
  - Simple structure
  - No need for snubber circuits
  - Requires only one DC source
  - Can deliver both active and reactive power
  - Requires many capacitors!

It seems that MMC is an ideal choice for our application

MMC (Cntd…)

- An n-level, single-phase MMC consists of:
  - *A series connection of* $2(n-1)$ *basic sub-modules (SMs)*
  - *Two buffer inductors*
  - *Each Sub-module (SM):*
    - Two switches and a capacitor
    - The output voltage of each SM switches between:
      - Its capacitor voltage (V_c): The SM is so-called ON
      - Zero : The SM is so-called OFF
- A complicated control method is needed to maintain balanced capacitor voltages

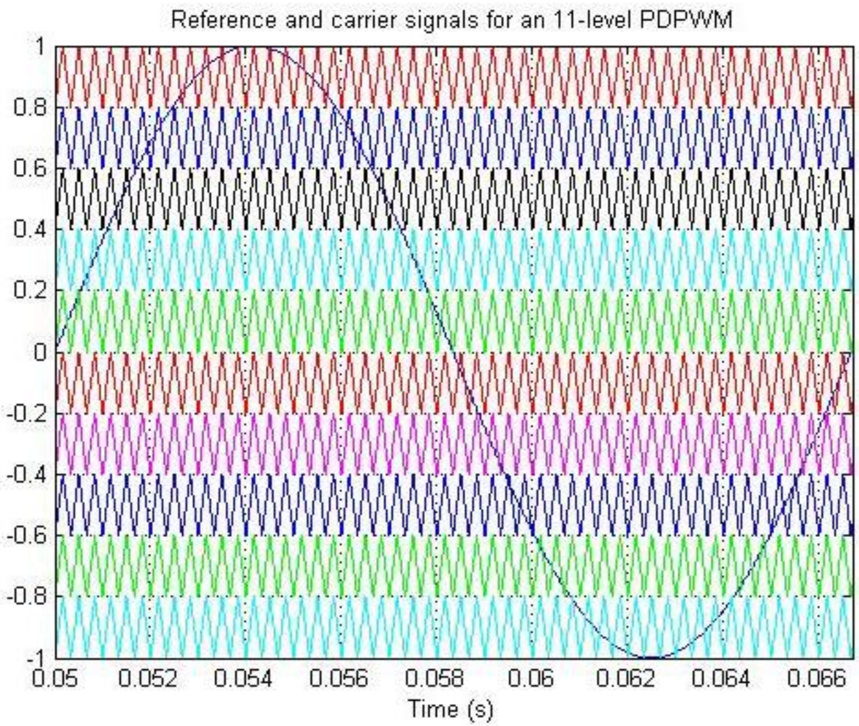
MMC (Cntd…)



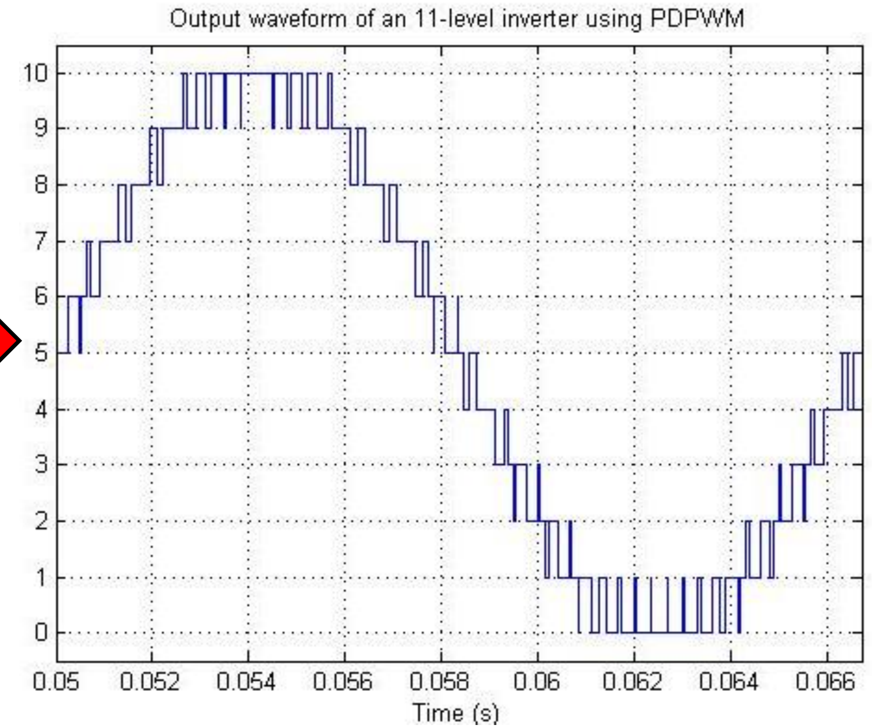
Configuration of the MMC topology

Configuration of each sub-module (SM)

Phase Disposition PWM (PDPWM)Technique



PDPWM technique for an 11-level inverter

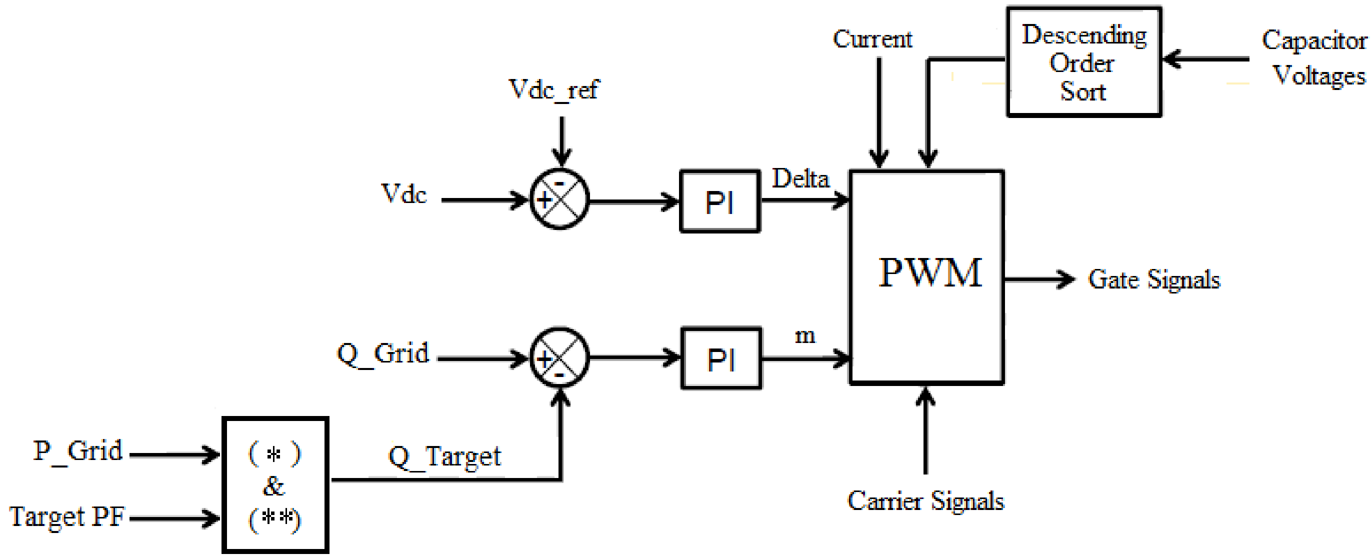


Output Voltage

Proposed Control Strategy

- The active and reactive power flow of the D-STATCOM inverter is governed by:

$$P_S = \frac{mE_S E_L}{X} \sin \delta \quad (*) \quad \text{and} \quad Q_s = \frac{mE_S E_L \cos \delta - E_L^2}{X} \quad (**)$$



The proposed control strategy for MMC D-STATCOM inverter

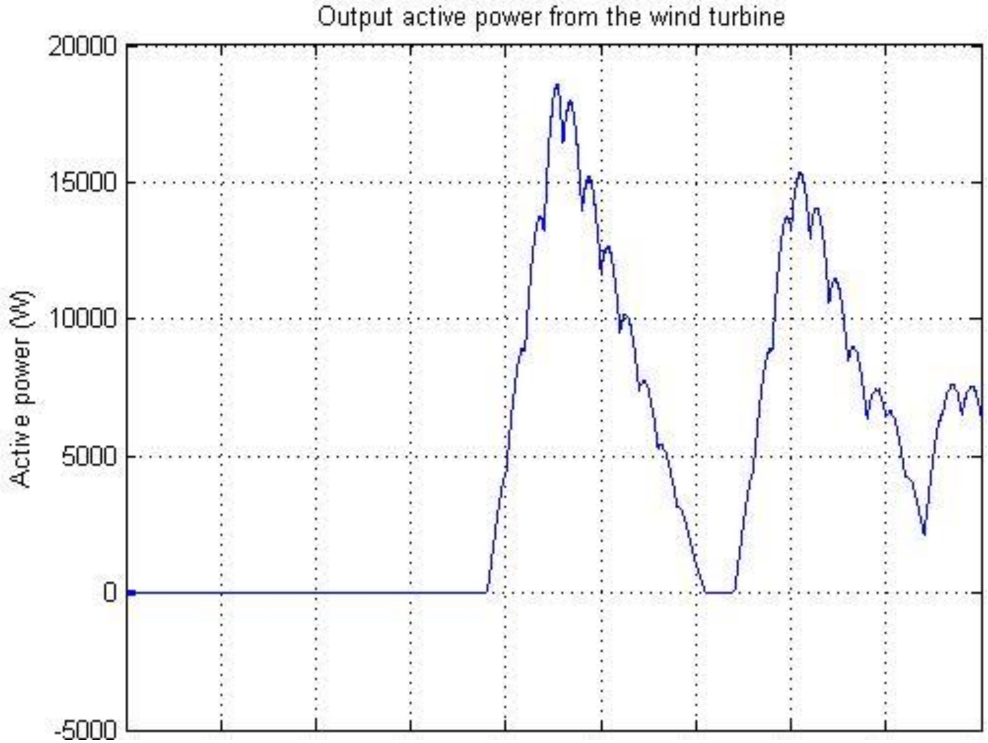
Simulations

Parameter	Value for 5-level model	Value for 11-level model
L_{line}	1 mH	1 mH
R_{line}	1 Ohm	1 Ohm
L_{filter}	25 mH	20 mH
C_{filter}	90 uF	70 uF
Transformer power rating	25 kVA	25 kVA
Transformer primary voltage	12000 V	12000 V
Transformer secondary voltage	600 V	600 V
Switching frequency	4 kHz	3 kHz
Target PF	0.80, 0.90, 0.95	0.80, 0.90, 0.95
DC link reference value	2500 V	2000 V
Initial voltages of DC link capacitors	1250 V	1000 V
Initial voltages of SM capacitors	625 V	200 V
Transformer inductance	$R_1 = 0.001\, p.u., L_1 = 0.001\, p.u.$ $R_2 = 0.001$ p.u., $L_2 = 0.002\, p.u.$	$R_1 = 0.001\, p.u., L_1 = 0.001\, p.u.$ $R_2 = 0.001$ p.u., $L_2 = 0.002\, p.u.$

Parameter values used for simulations

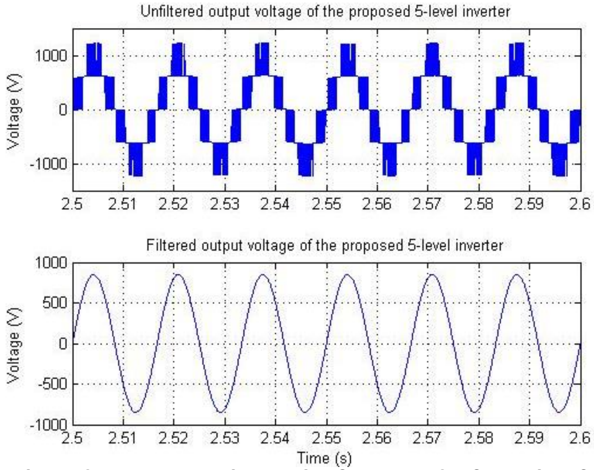
Simulations (Cntd…)

Time (s)	Loads	Load P & Q	Load PF	Target PF
0	1	50 kW, 35 kVAR	0.82	0.90
1	1	50 kW, 35 kVAR	0.82	0.90
2	1	50 kW, 35 kVAR	0.82	0.90
3	2	50 kW, 28 kVAR	0.87	0.90
4	2	50 kW, 28 kVAR	0.87	0.90
5	2	50 kW, 28 kVAR	0.87	0.90
6	2+3	60 kW, 31 kVAR	0.89	0.90
7	2+3	60 kW, 31 kVAR	0.89	0.90
8	2+3+4	65 kW, 42 kVAR	0.84	0.90
9	2+3+4	65 kW, 42 kVAR	0.84	0.90
10	2+4	55 kW, 39 kVAR	0.81	0.90
11	2+4	55 kW, 39 kVAR	0.81	0.90
12	2	50 kW, 28 kVAR	0.87	0.90
13	2	50 kW, 28 kVAR	0.87	0.90
14	1	50 kW, 35 kVAR	0.82	0.90
15	1	50 kW, 35 kVAR	0.82	0.90
16	1	50 kW, 35 kVAR	0.82	0.90
17	1	50 kW, 35 kVAR	0.82	0.90
18	1	50 kW, 35 kVAR	0.82	0.90
19	1	50 kW, 35 kVAR	0.82	0.90
.	.	.	.	.
.	.	.	.	.
43	1	50 kW, 35 kVAR	0.82	0.90
44	1	50 kW, 35 kVAR	0.82	0.90

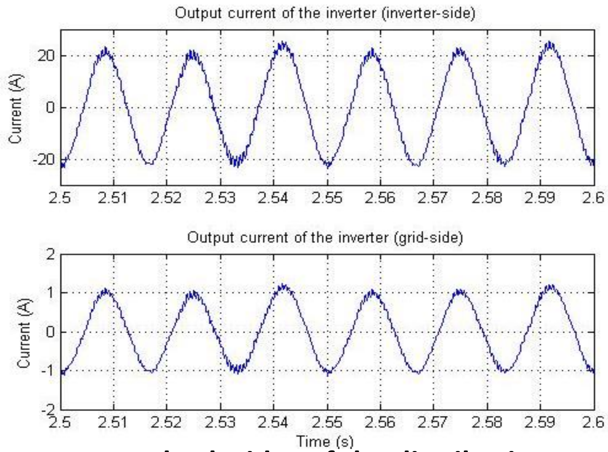


Output active power from the wind turbine: 45-second simulation

Simulation Results for 5-level Model

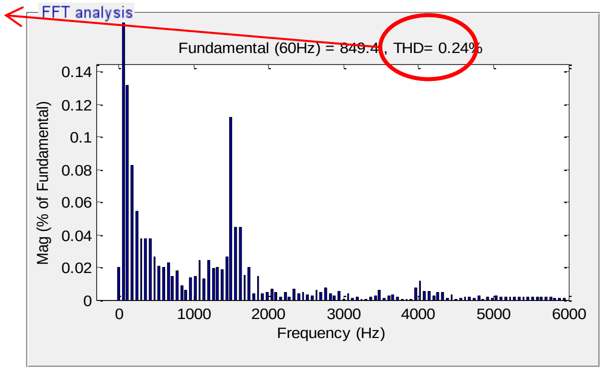


Simulated output voltage before and after the filter

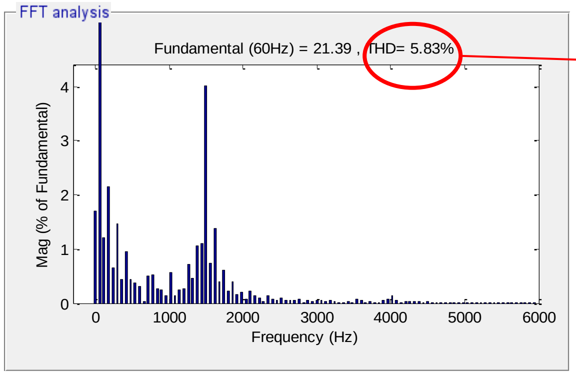


Output current on both sides of the distribution transformer

0.24%



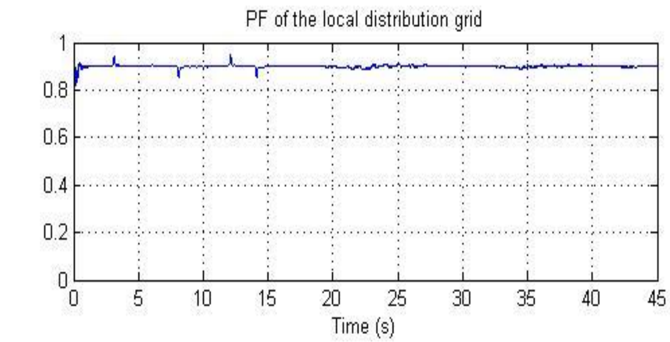
FFT of the filtered output voltage of the 5-level inverter



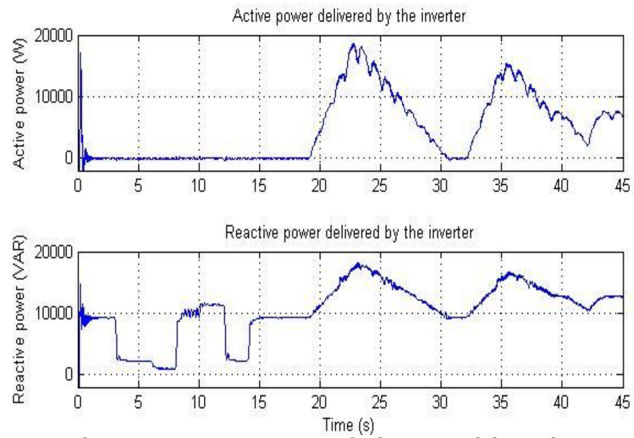
5.83%

FFT of the inverter-side current

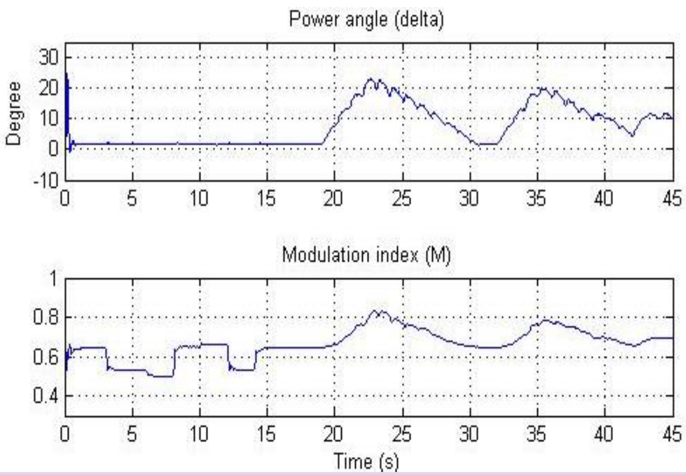
Simulation Results for 5-level Model (Cntd…)



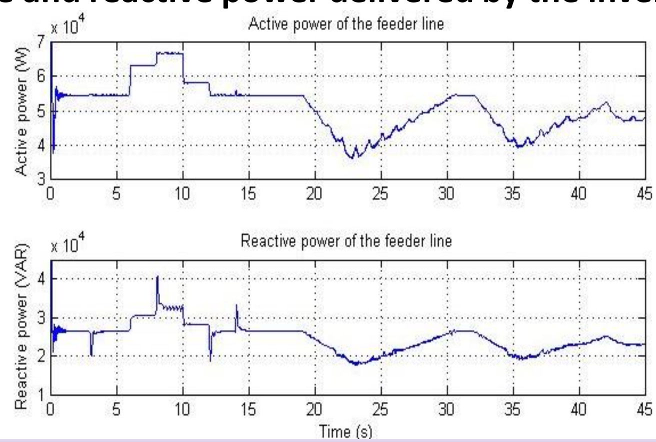
PF of the local distribution grid



Active and reactive power delivered by the inverter

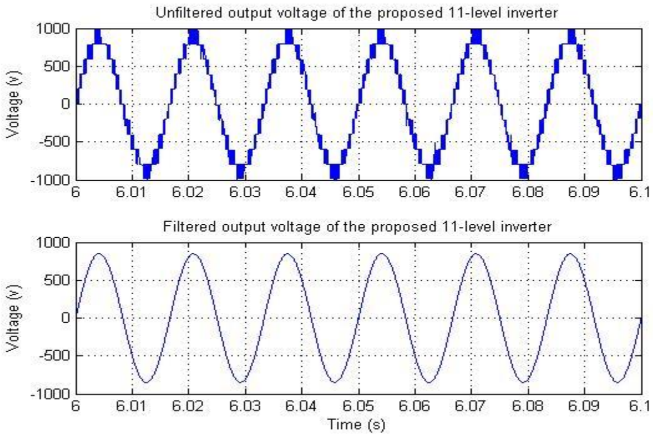


Power angle and modulation index of the inverter

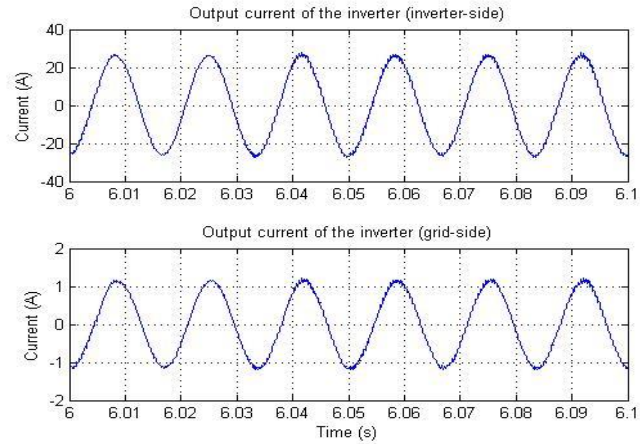


Active and reactive power of the feeder line

Simulation Results for 11-level Model

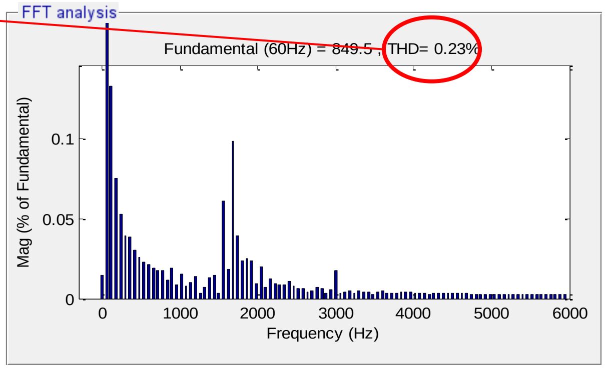


Simulated output voltage before and after the filter



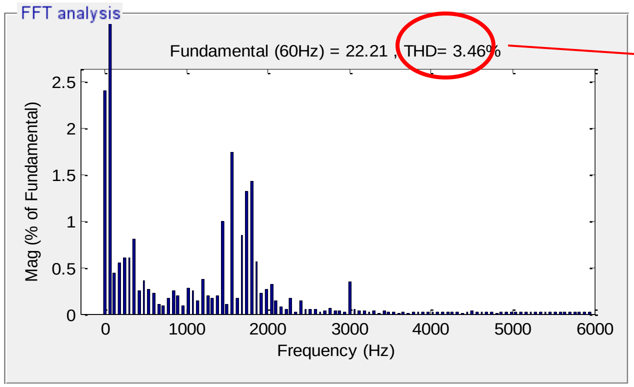
Output current on both sides of the distribution transformer

0.23%



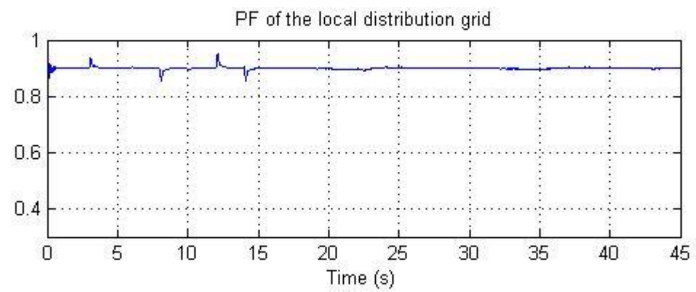
FFT of the filtered output voltage of the 11-level inverter

3.46%

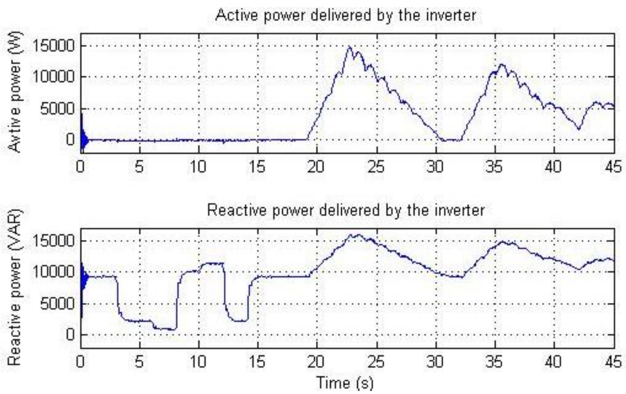


FFT of the inverter-side current

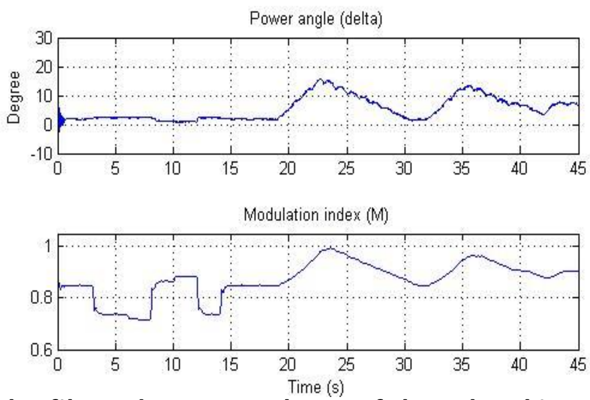
Simulation Results for 11-level Model (Cntd…)



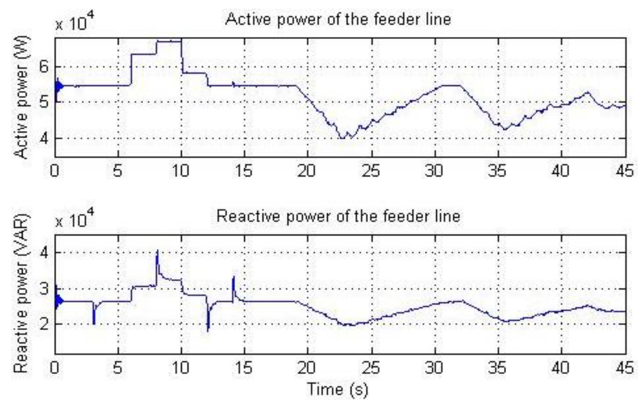
Simulated output voltage before and after the filter



Output current on both sides of the distribution transformer

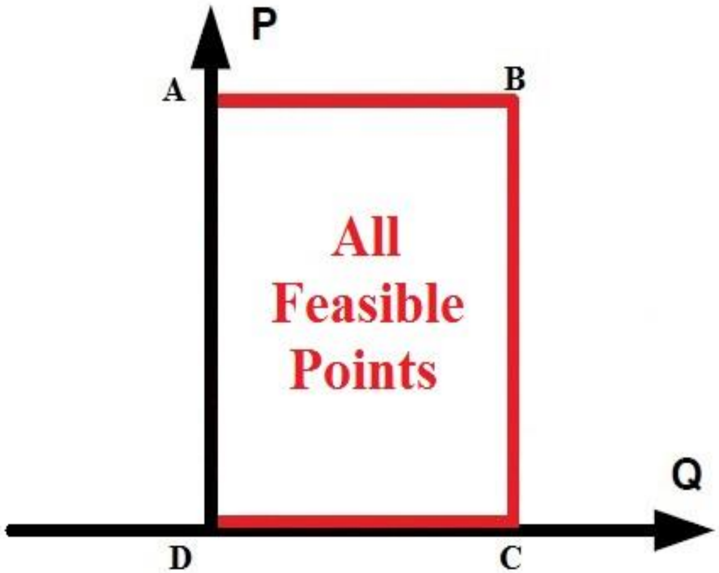


FFT of the filtered output voltage of the 5-level inverter

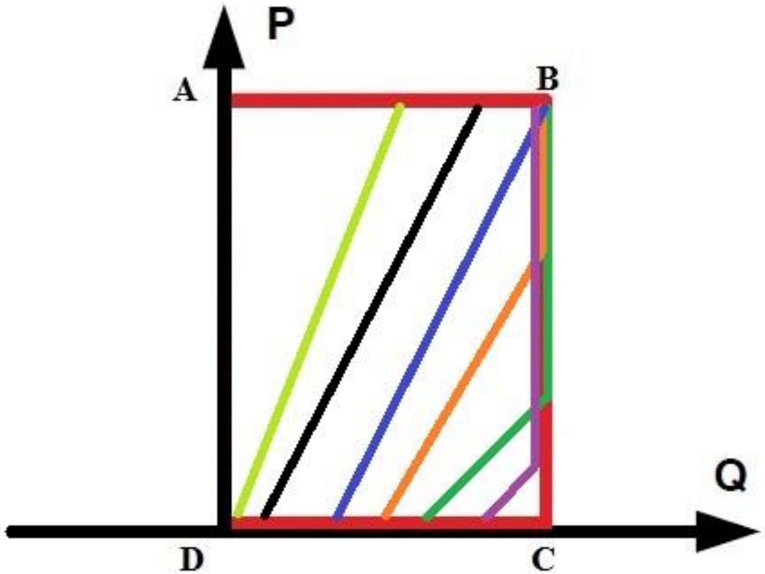


FFT of the inverter-side current

PQ Diagrams



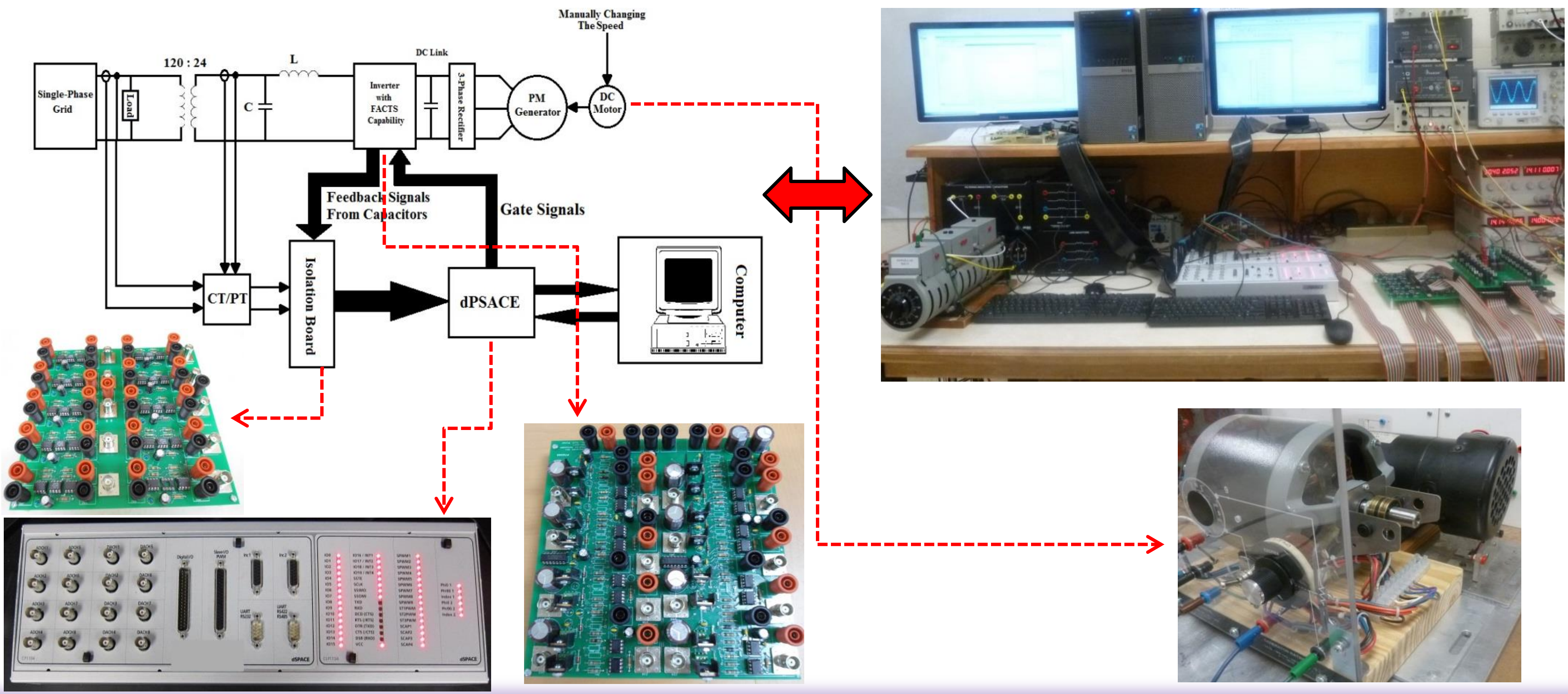
P-Q diagram of the proposed inverter in terms of device's capability



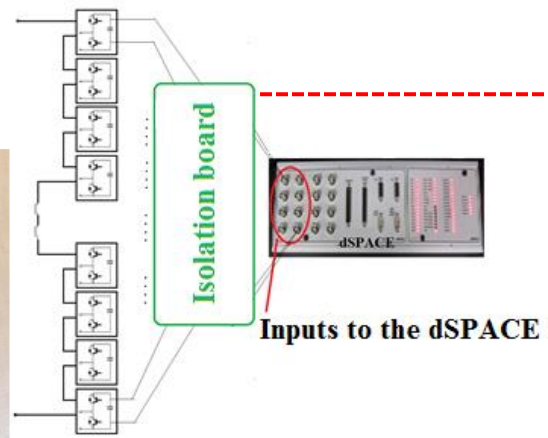
P-Q diagram of the system considering the operating conditions

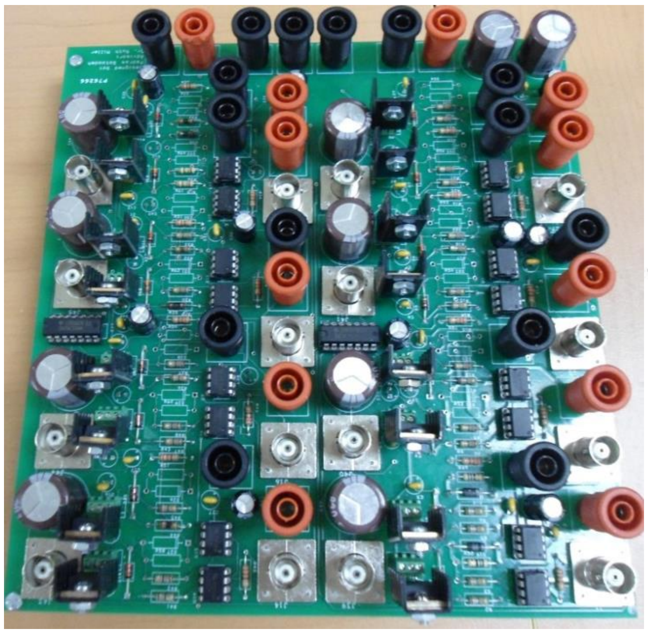
Setup Implementation

- A 5-level and 11-level model of the system has been built and tested

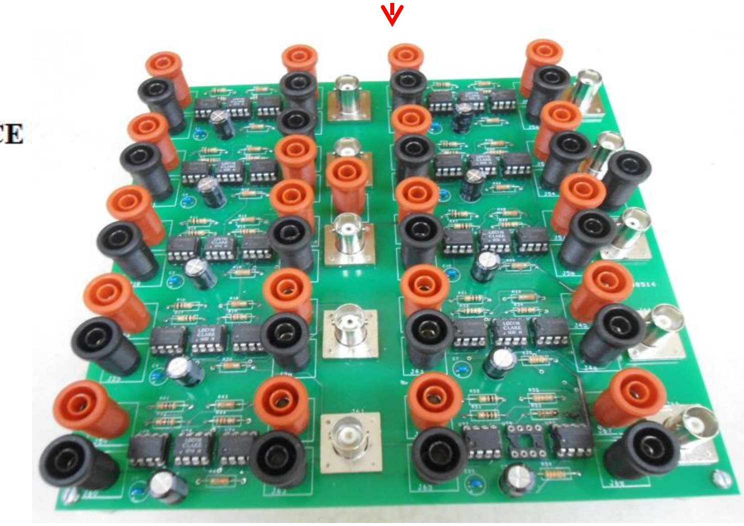


Setup Implementation (Cntd…)



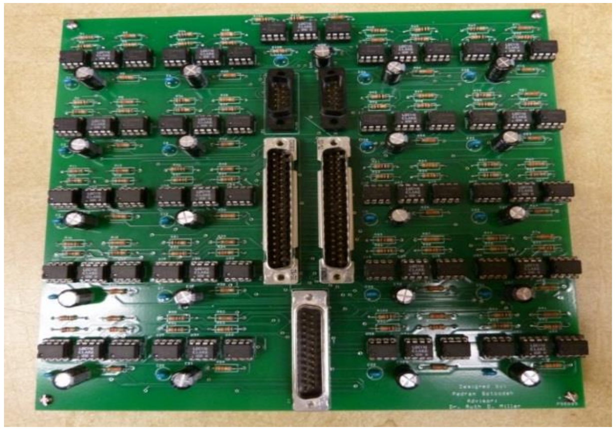


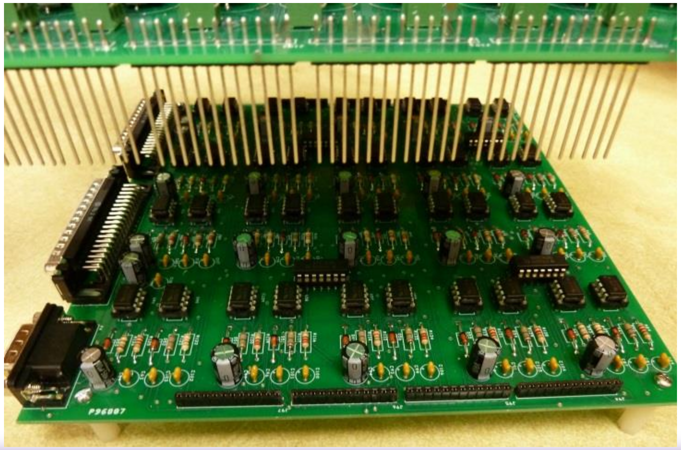
5-level reduced scale model

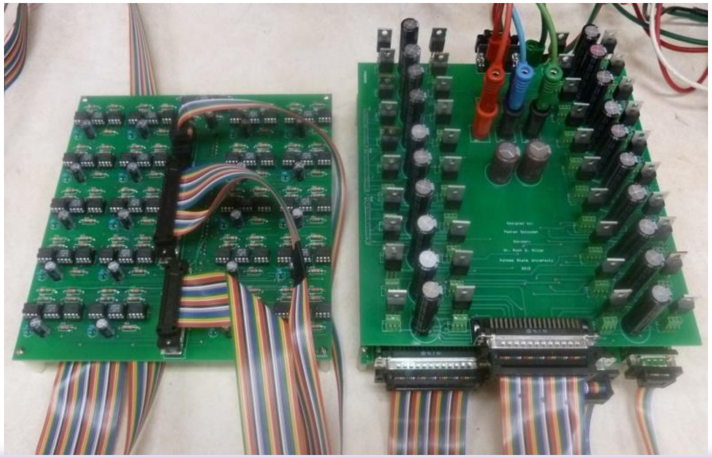


The opto-coupler isolation board designed for the 5-level system

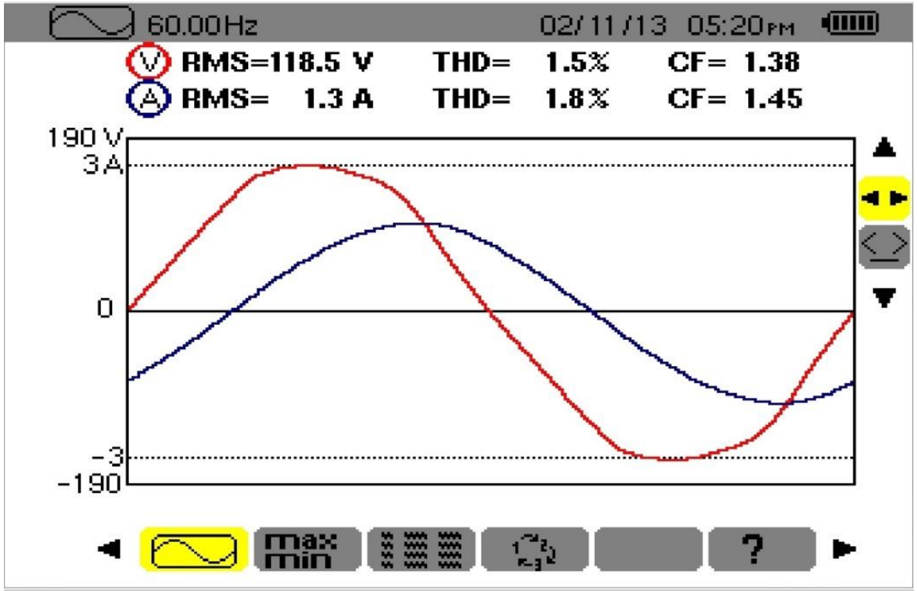
Setup Implementation (Cntd…)



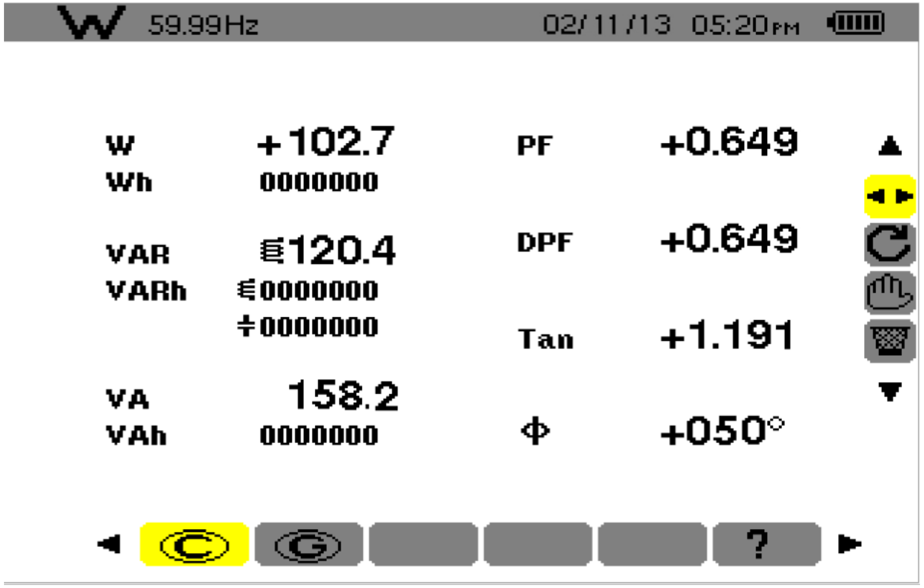




Experimental Results

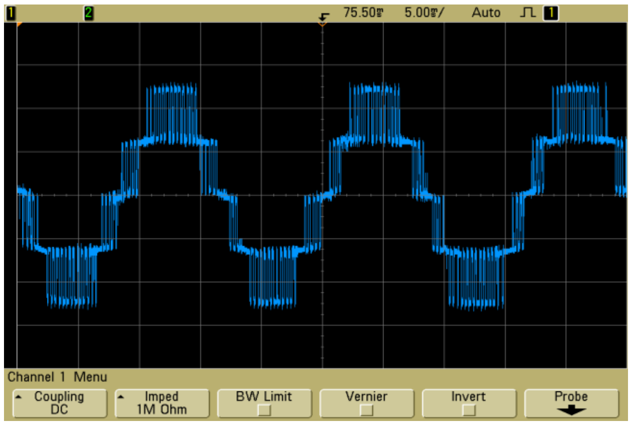


Voltage and current waveforms of the grid before compensation

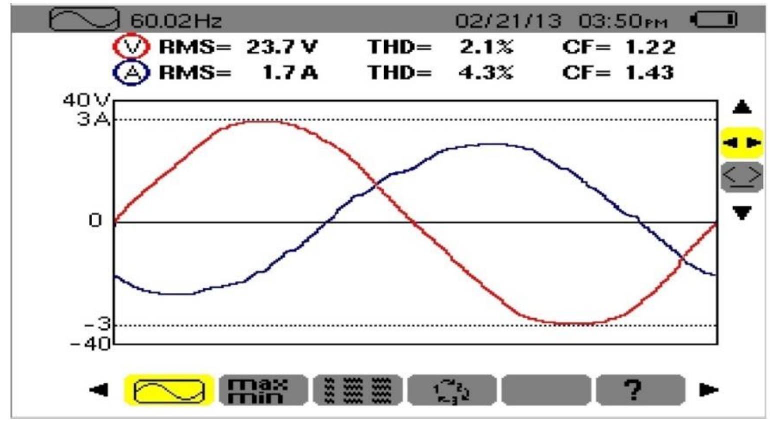


Active power, reactive power, and PF of the grid before compensation

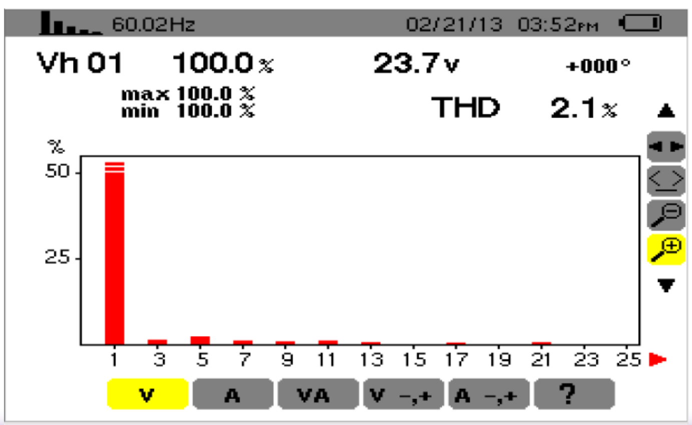
Experimental Results (Cntd...)

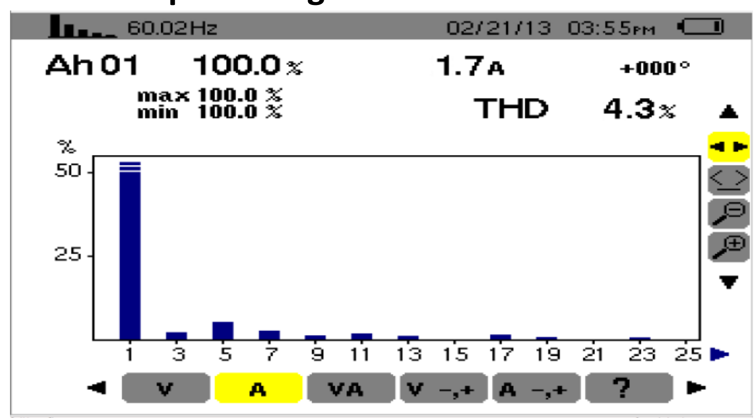


Unfiltered output voltage of the 5-level inverter



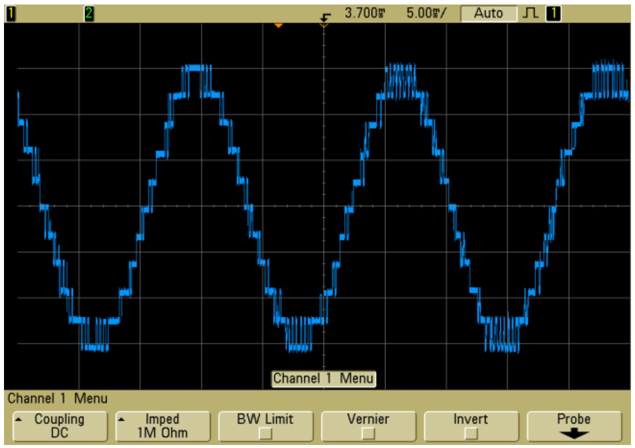
Filtered output voltage and current of the 5-level inverter



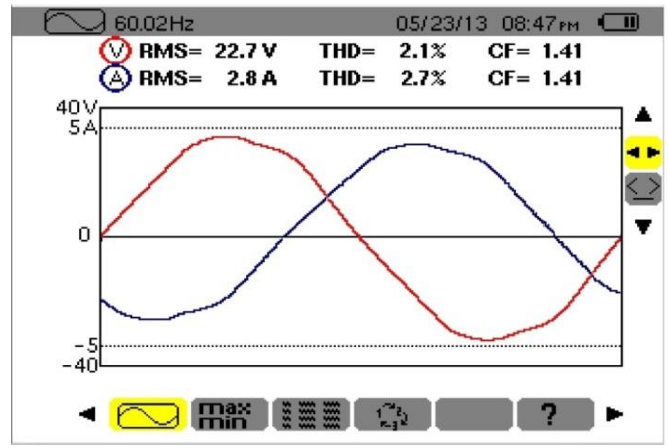


THD of the filtered output voltage and current of the 5-level inverter

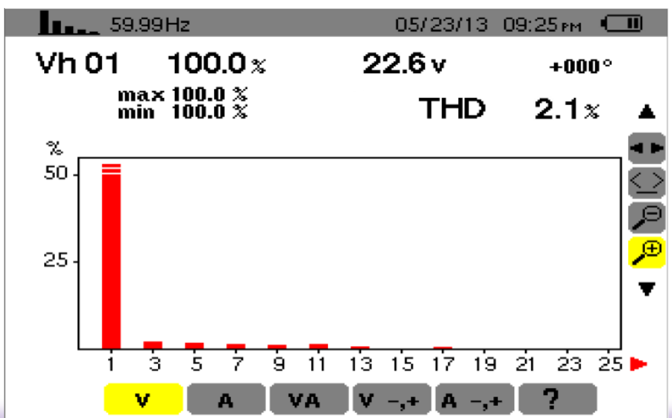
Experimental Results (Cntd…)

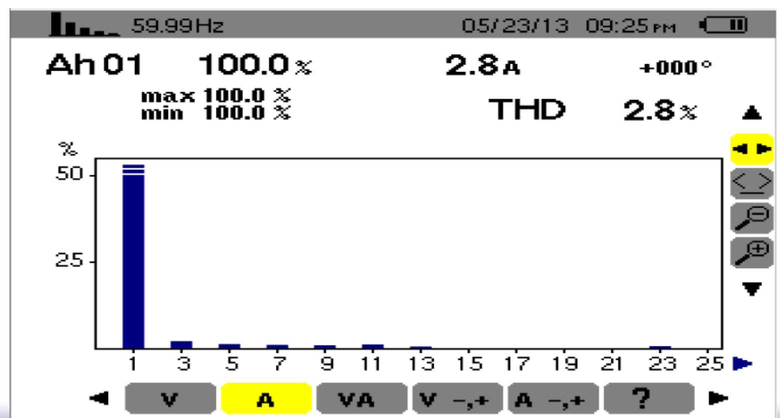


Unfiltered output voltage of the 11-level inverter



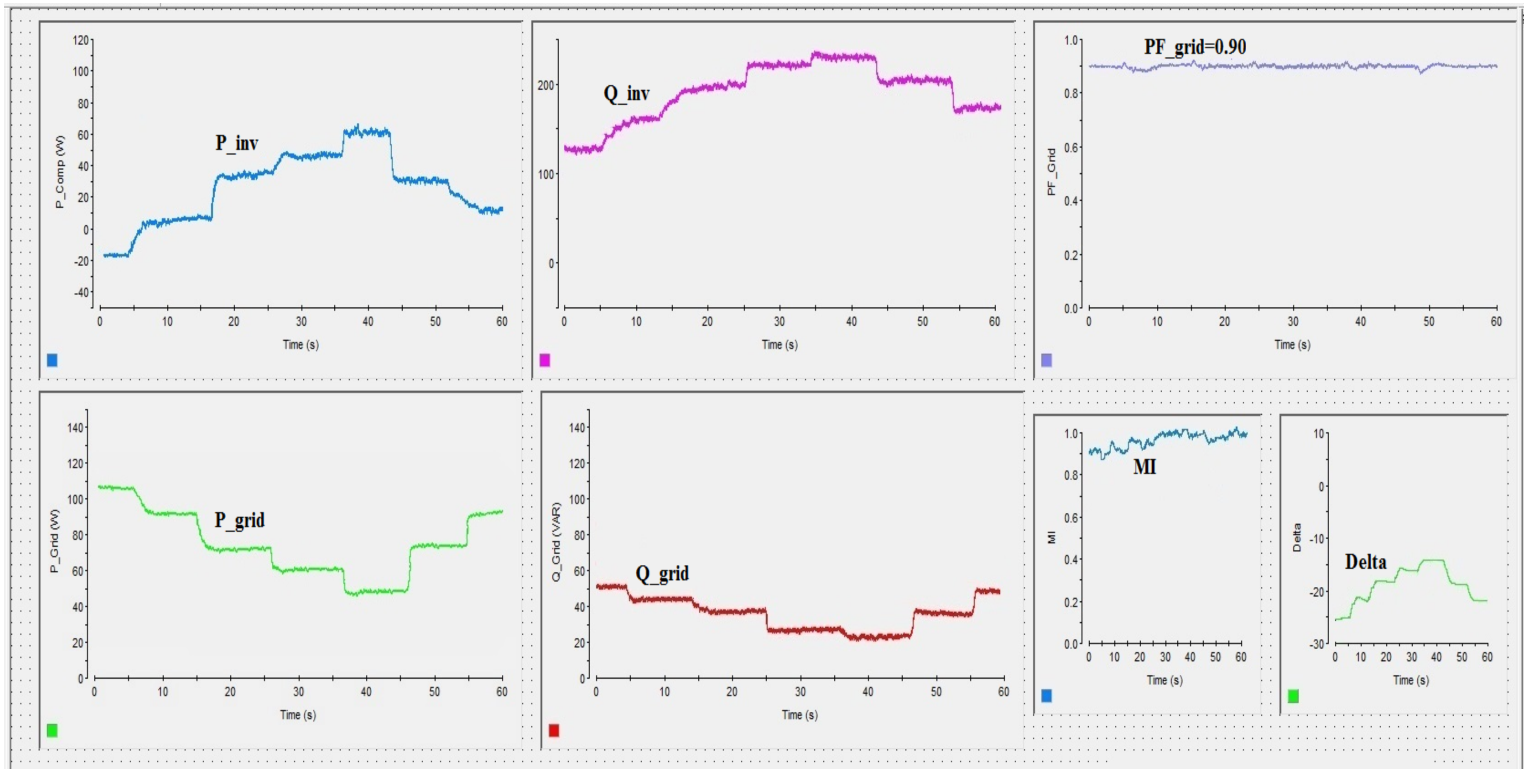
Filtered output voltage and current of the 11-level inverter





THD of filtered output voltage and current of the 11-level inverter

Experimental Results (Cntd...)



System parameters after compensation when wind is blowing (Target PF=0.90)

Comparison Between 5- and 11-level Experiments

Parameter	5-level Model	11-level Model
Output Filter	10 mH, 25 uF	2.5 mH, 12 mF
Switching Frequency	3 kHz	2 kHz
Efficiency	93%	94%
Distribution Transformer	120:24	120:24
Current THD	4.2%	2.7%
Voltage THD	2.1%	2.1%
Compatibility with IEEE 519 Standard	Yes	Yes

Cost Comparison Between 5- and 11-level Prototype Models

Component	5-level model	11-level model	Cost: 5-level	Cost: 11-level
SMs capacitor	8 (50 V, 1000 uF) Each: $ 0.94	20 (25 V, 1000 uF) Each: $ 0.23	~ $ 8	~ $ 5
DC link capacitor	2 (50 V, 1000 uF) Each: $ 0.94	2 (50 V, 1000 uF) Each: $ 0.94	~ $ 2	~ $ 2
Arm inductor	2 (5 mH, 1 A) Each: $ 30	2 (5 mH, 1 A) Each: $ 30	~ $ 60	~ $ 60
Power Switch	16 (IRF 510) Each: $ 0.91	40 (IRF 510) Each: $ 0.91	~ $ 16	~ 40
Gate Drive Module	16 HCPL 3120, resistors, Schottkey & Zener diodes Each: ~ $ 5	40 HCPL 3120, resistors, Schottkey & Zener diodes Each: ~ $ 5	~ $ 80	~ $ 200
PC Board	$ 66 (2 Boards)	$ 99 (3 Boards)	~ $ 66	~ $ 99
Isolation Module	8: opto-coupler, resistors, diodes, capacitors. Each: $ 3	20: opto-coupler, resistors, diodes, capacitors. Each: $ 3	~ $ 24	~ $ 60
Miscellaneous connectors, sensors	including 14A-2.5R12, 13/10TALEMA, connectors Each: $ 20	including 14A-2.5R12, 13/10TALEMA, connectors Each: $ 50	~ $ 20	~ $ 50
Total			~ $ 275	~ $ 515

Cost Comparison Between Proposed Inverter and Conventional Inverters

Power Rating	5-level model	11-level model	Market Price
250 W	~ $ 275	~ $ 515	$ 200-400
1 kW	~ $700	~ $ 1250	$ 600- $ 800
3 kW	~ $1500	~ $ 2650	$ 1400- $ 1600
10 kW	~ $ 2500	~ $ 4400	$ 3750- $ 4500
20 kW	~ $ 3500	~ $ 6100	> $ 5200

Conclusion

- The concept of a D-STATCOM inverter is presented.
- The MMC D-STATCOM inverter has the ability to provide utilities with capacitive VAR compensation.
- The unique work of this research is to combine the two concepts of D-STATCOM and inverter using the most advanced multi-level topology to make a single unit called D-STATCOM inverter.
- The proposed MMC inverter is not only able to transfer active power, but is able to control the power factor (PF) of the distribution system (FACTS capability).
- The proposed inverter cost is comparable with market price, however, it has more functionality and options.

Future Work

- Implementing of higher-rated inverters by using higher-rated components
- Implementing the proposed inverter using a microcontroller such as digital signal processor (DSP)
- Other multi-level topologies could be chosen to design the proposed inverter

Questions?

Thank you!