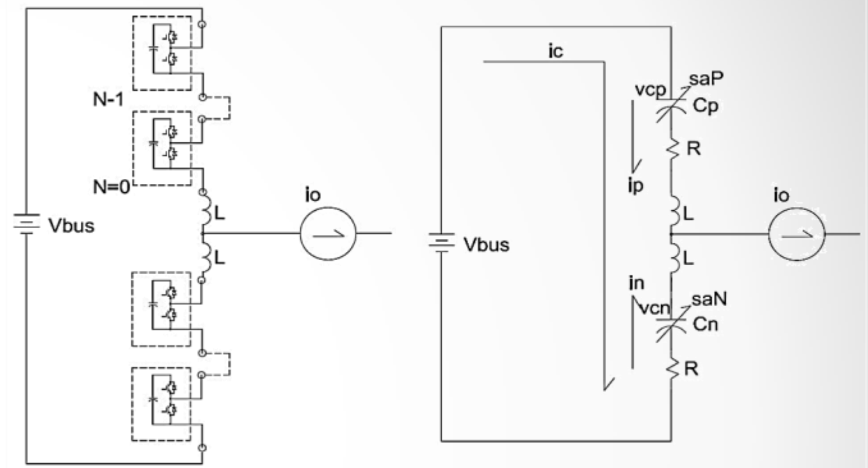
High Resonant Frequency M2LC Topology for Motor Drive and Energy Sector Applications

Abstract

- The Modular Multilevel Converter (M2LC) topology has been recently introduced as an alternative HVDC transmission system
- Inherent characteristics of the topology have prevented its use in industrial motor control applications until recently
- A breakthrough has been achieved that overcomes these limitations allowing the M2LC to become the new paradigm for AC motor drives as well as for application in energy sector power control and transmission systems
- This presentation describes a new approach to M2LC power circuit design that enabled this breakthrough to be achieved and reduced to practice
- The results are dramatic and provide an overall smaller, more efficient and more cost effective design
- To mechanize and control this new AC motor control inverter, a state-of-the-art control Hub with fault-tolerant, optical communications was developed that offers substantial advantages over conventional control implementations
- Highlights from real-world installations using the new M2LC design techniques will be presented to illustrate the practicality of the design approaches

Dynamical Model of the M2LC

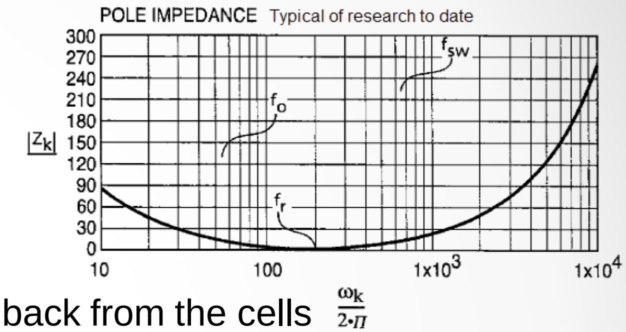
- Developed by researches at the Royal Institute of Technology (KTH), Stockholm, Sweden [1,2,3]
- Provides a simple model to predict all electrical and control aspects of the M2LC
- Used to model and verify a new variation of the M2LC that operates with relatively high pole resonant frequency with respect to output and cell switching frequencies
- Allows for the development of a modulator that completely controls both the average and fundamental ripple voltage on the cell filter capacitors



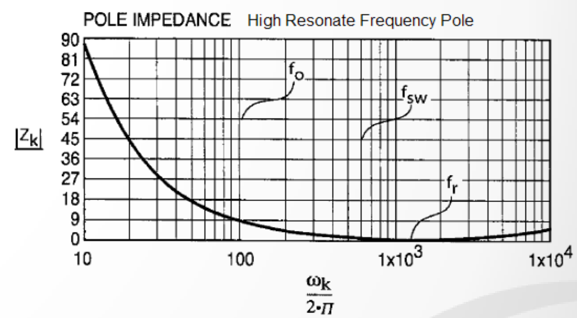
$$\begin{pmatrix} ic_{k+1} \\ vcp_{k+1} \\ vcn_{k+1}\end{pmatrix} := \begin{pmatrix} 1-\frac{R}{L}\cdot\delta & \frac{-saP_k}{2\cdot L}\cdot\delta & \frac{-saN_k}{2\cdot L}\cdot\delta \\ \frac{saP_k\cdot N}{C}\cdot\delta & 1 & 0 \\ \frac{saN_k\cdot N}{C}\cdot\delta & 0 & 1\end{pmatrix}\cdot\begin{pmatrix} ic_k\\ vcp_k \\ vcn_k\end{pmatrix} + \begin{pmatrix}\frac{Vbus\cdot N}{2\cdot L}\cdot\delta \\ \frac{saP_k\cdot ioa_k\cdot N}{2\cdot C}\cdot\delta \\ \frac{-saN_k\cdot ioa_k\cdot N}{2\cdot C}\cdot\delta\end{pmatrix}$$

High Resonant Pole Frequency M2LC

- The previously established design rule for the M2LC has been to size the inter-arm reactors large enough to minimize unwanted 2nd and other even harmonic components, which can be induced in the arms of M2LC for sinusoidal outputs:
  - This results in inherent instability that must be controlled to actively balance the in the filters in each arm using active feedback from the cells



- Sizing the reactors large enough to eliminate the 2nd harmonic component has other drawbacks:
  - Adds a significant voltage drop from the available DC bus voltage subsequently requiring higher source KVA
  - Extra cells must be added that contribute to overall losses
  - A higher degree of modulation is required to balance the average voltage on each arm capacitor

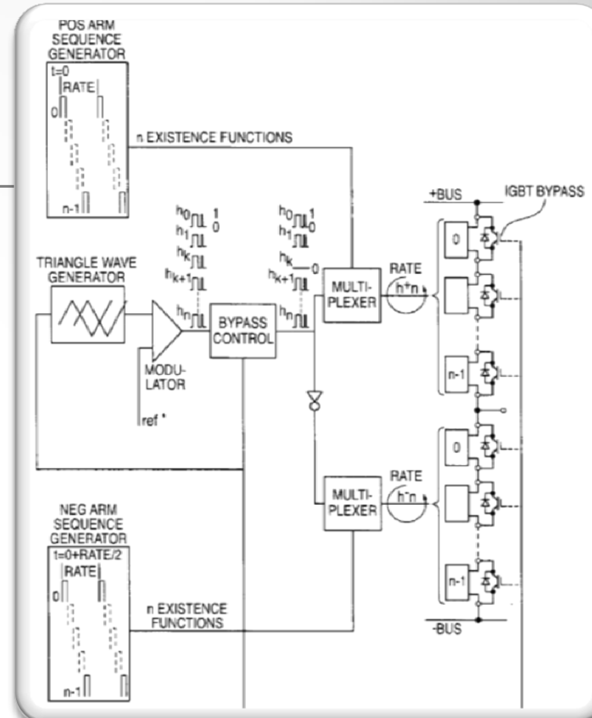


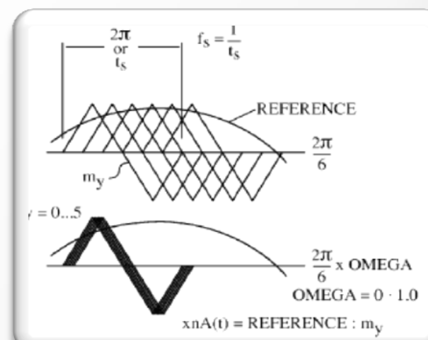
- Substantially reducing the typical inter-arm inductance by a factor of ~50-100 times to increase the resulting resonant frequency significantly above the switching frequency provides dramatic benefits:
  - Eliminates the need for active energy balancing
  - Eliminates the reactive voltage drop
  - Maximizes the available cell voltage to produce fundamental output voltage [2]
  - Minimizes the required number of cells and their associated losses

![REGAL]

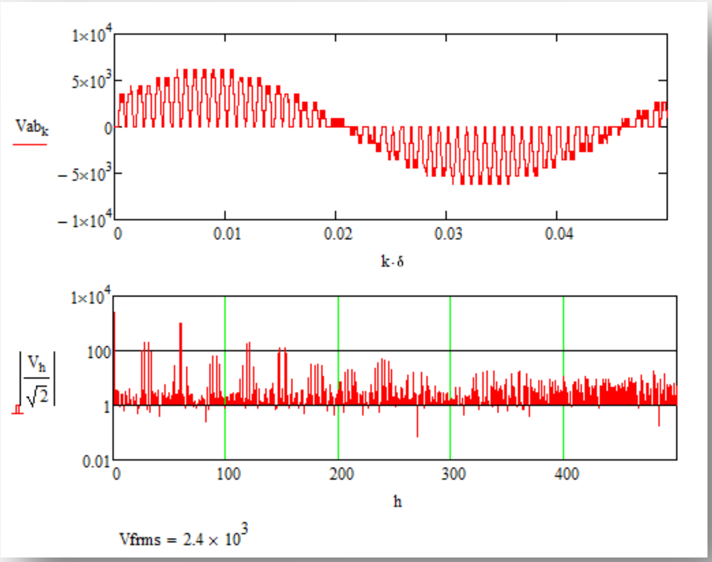
M2LC Modulator

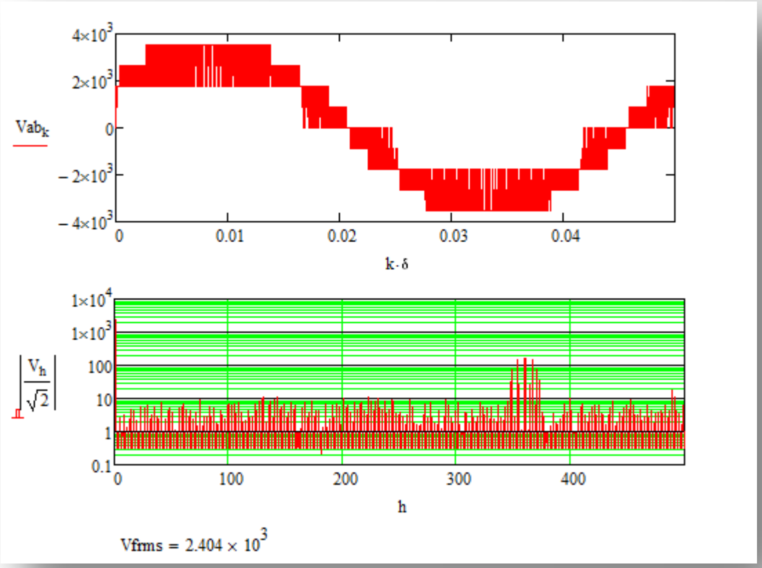
- Control of both the average and fundamental ripple voltage of the cell capacitors is done completely in the modulator
- Periodic re-assignment of switch functions [4] allows for auto-balancing of capacitor voltage even with no load current
  - Also allows for injecting a “0” state for cell redundancy [4]
- Phase shift control of the switch functions allows for pseudo 2-level operation which cancels a majority of the capacitor fundamental current [5]
- Since the pole resonance is high, this can be done at the switching frequency without injecting intermediate frequency





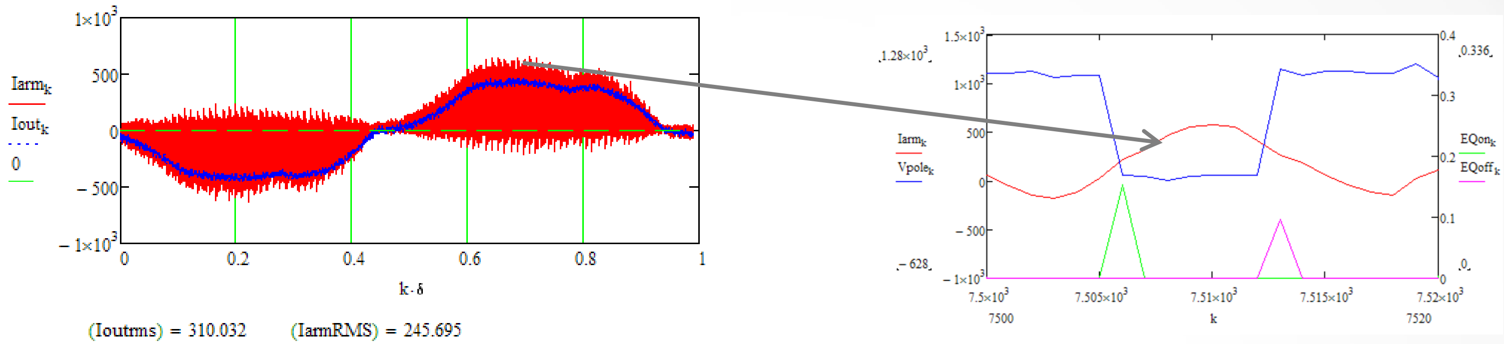
M2LC Modulator @ 20Hz





- Advantages of gate phase shifting common mode modulation scheme
  - Fundamental voltage is preserved
  - Output distortion is minimized to side bands around cell switching frequency (typically 600Hz)
  - Common mode voltage is basically a sinusoidal waveform at the carrier frequency with steps no greater than the cell filter voltage

Performance @ 1Hz



(Ioutrms) = 310.032 (IarmRMS) = 245.695

(CellLoss) = 875.66

(Total_Switching_Loss) = 245.394

(Total_Conduction_Loss) = 630.266

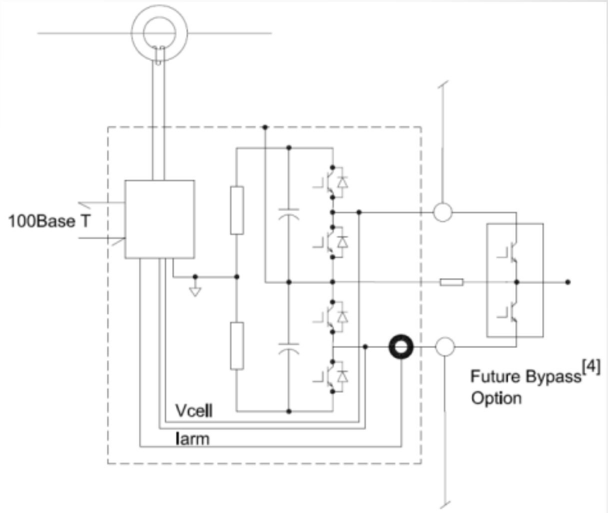
M2LC_%loss = 0.774

Detail of Arm Current, IGBT Voltage, and Switching Energies

- Additional advantages of common mode developed by phase shifting:
  - High quality output current at very low frequencies
  - Essentially no generation of DC component in output current
  - Near zero current switching allowing for minimum loss increase

M2LC Power Cell Visibility

- In addition to providing capacitor voltage control and stable operation at low frequencies, one of the biggest challenges faced applying the M2LC topology for a practical ac motor drive application was to improve the cell visibility to the Hub control system
- A novel current source subsystem [6] was devised and applied to provide control power to the cells under all normal and abnormal operating conditions
- This feature provided a convenient pre-charge approach that enabled the IGBTs in each cell to be gated (for 0 ac output voltage) at the onset of the pre-charge event thereby charging the cell capacitors to the proper operating voltage condition
- The proven implementation is simple, robust and highly reliable



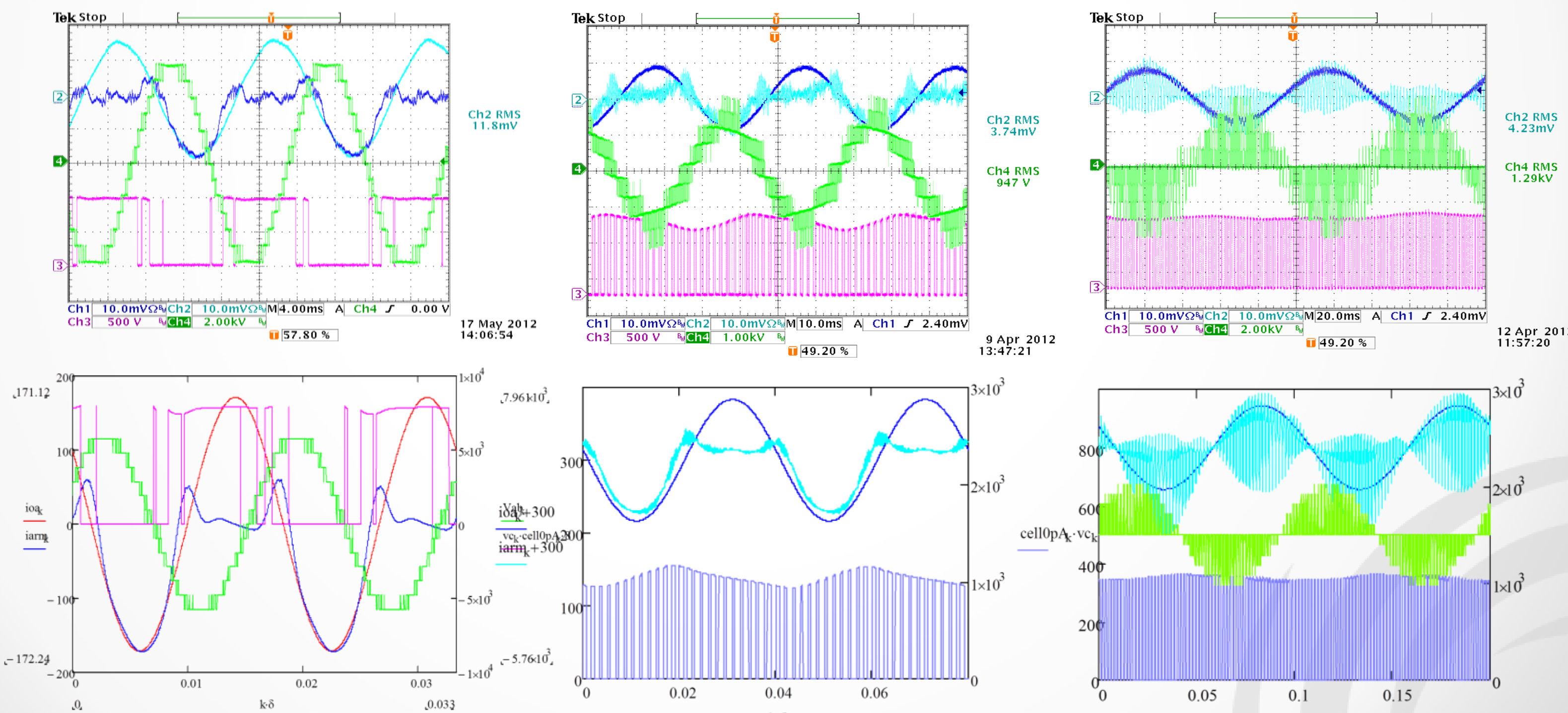
M2LC Cell

Lab and Simulation Results

- Actual measurements agree well with the KTH dynamical model over all operating conditions
- Phase shifting the gate functions between 10-30% of optimum proved to be extremely effective in controlling capacitor ripple voltage at low frequency with greater than rated current down to and including 0Hz

Measured

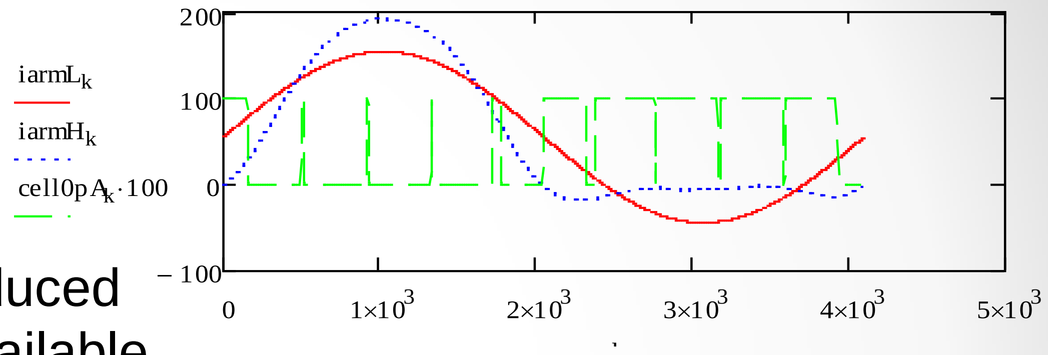
Modeled



60Hz 25Hz 10Hz

Performance of an M2LC with High Resonant Pole Frequency

- Operating an M2LC with very small inter-arm inductances does not appreciably impact cell losses
- RMS capacitor currents are reduced by 33% while allowing more available average voltage to be delivered to the load
- The overall net performance impact with a high resonance design is that inter-pole inductor voltage and power losses are essentially eliminated and cell capacity can be optimally utilized allowing for very high efficiency:
  - 99.4% has been demonstrated successfully for M2LC inverter



	Low Resonance Pole Design	High Resonance Pole Design
AVG(iarm)	55.1	55.1
MAX(iarm)	154	192
MIN(iarm)	-44	-19
RMS(iarm)	89	95
RMS(icap)	30	20

PigbtTop	14.1	4.9
PfwdTop	22.5	14.4
PigbtBot	118.8	127.7
PfwdBot	1.7	1.3
Ptotal (w)	157.1	148.3

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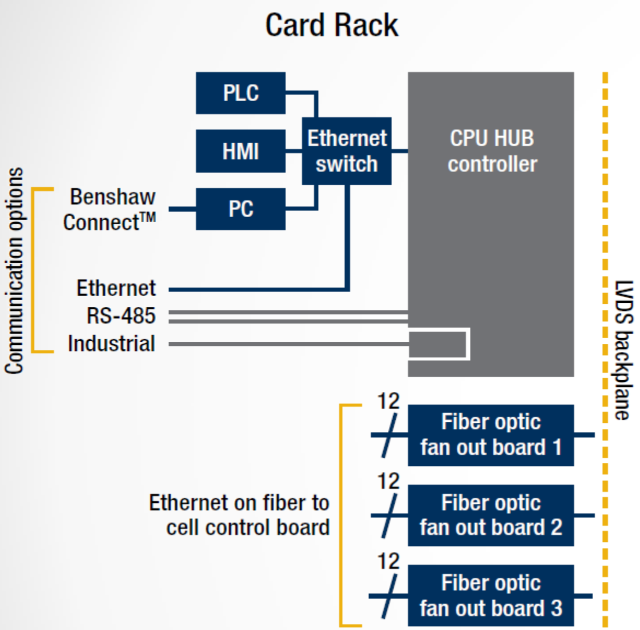
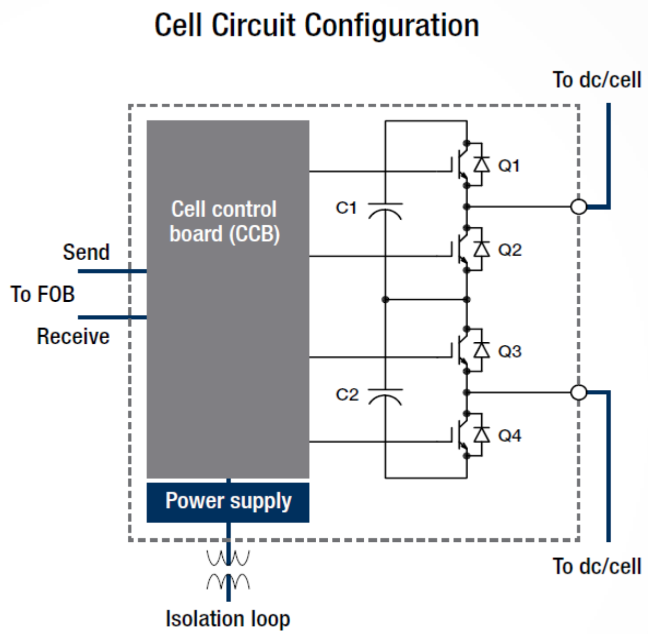
Hub and Cell Fan-out Control





- Texas Instrument-based ARM/DSP Hub Control
- FPGA-based Fan-Out boards for modulation and 100 Base T Ethernet Cell Communications
- Up to 48 Cell capability (2.3kV domestic to 11kV Asian applications)

Cell Communications and Status

A	B	C	CAP VOLTAGE Top	CAP VOLTAGE Bottom	VOLTAGE +5	VOLTAGE +15	IGBT TEMP Top	IGBT TEMP Bottom	PWB Temp
5	5	5	0023	0021	4.968	14.678	025	025	032
3	3	3	0024	0021	4.979	14.791	024	025	031
1	1	1	0025	0022	4.978	14.652	024	024	031
2	2	2	0023	0021	4.952	14.623	024	024	031
4	4	4	0024	0018	4.961	14.766	024	024	031
6	6	6	0025	0021	4.963	14.674	024	024	031

Main | Meter Values | Meter Trending | Param Settings | I/O Monitor | Cell Overview | RTD | Warnings & Lockouts | Start

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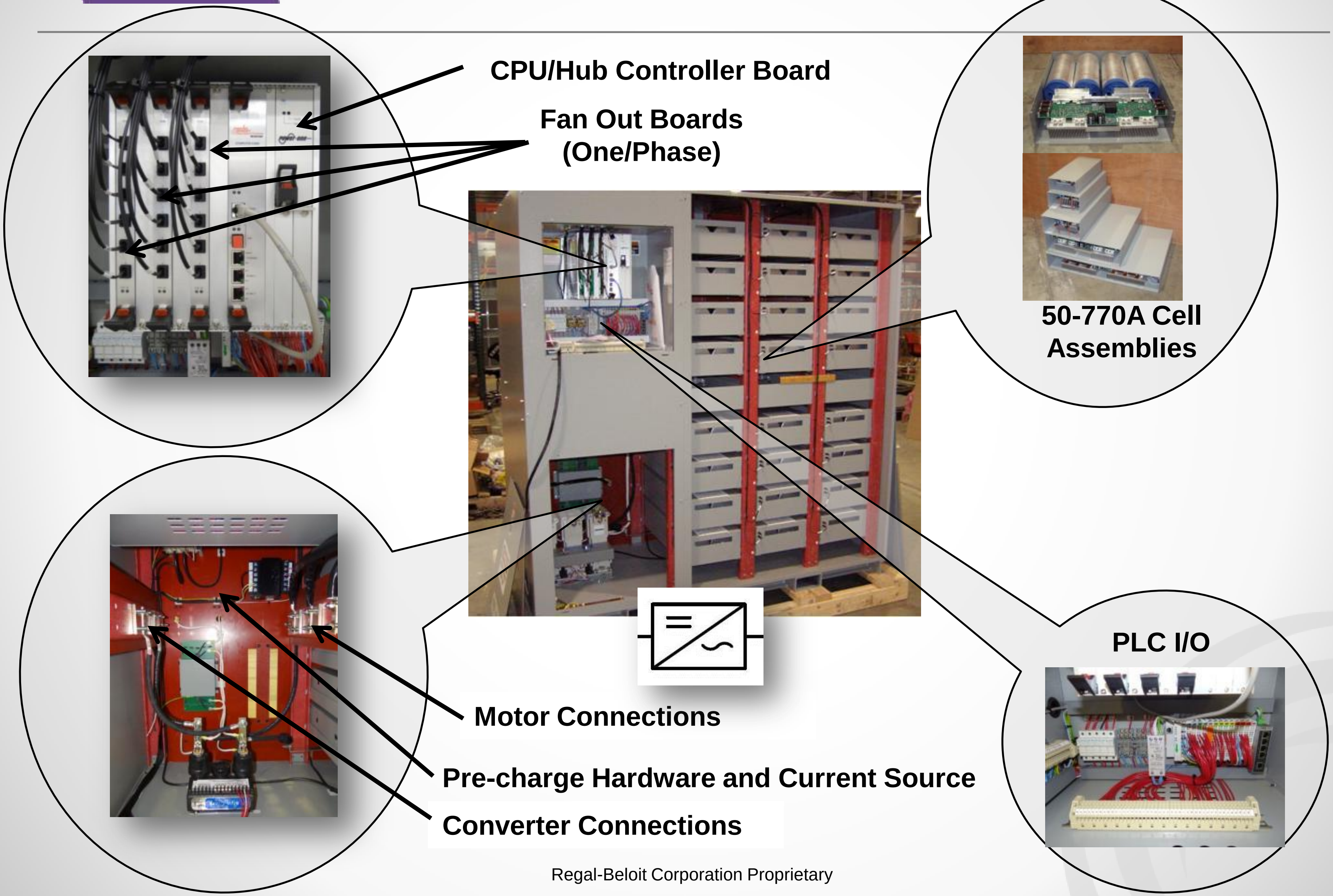
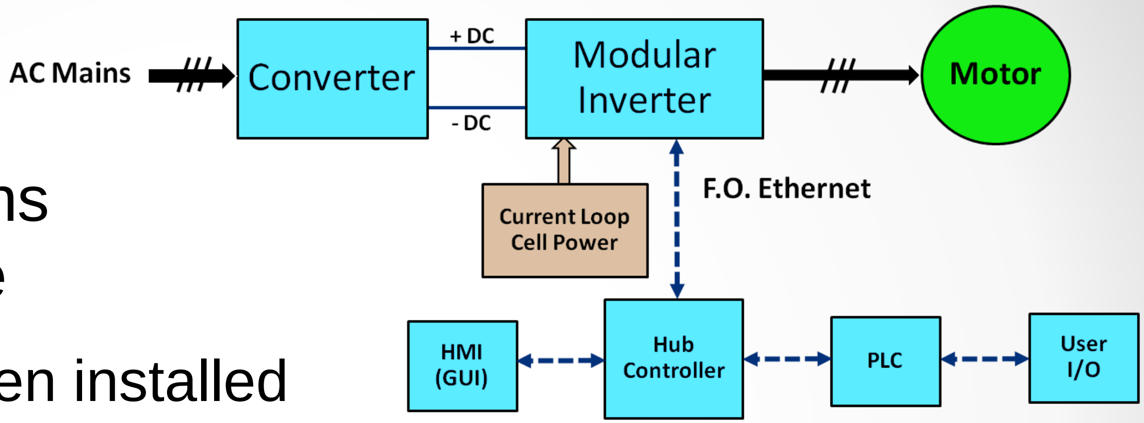
- All real time motor control and power circuit metrics are communicated between hub and cell over optical Ethernet
- No voltage or current sensors external to cells (no single point of failure)
- In addition to control variables, cell status is available real time under any operating condition

5.4kv, 2.8MVA, 9-Level M2LC System



M2LC — Reduced to Practice



- The M2LC topology has been applied in numerous applications as an AC motor drive
  - ~30 drives have been installed and are operating to date
  - Domestic and international installations
- Customers range from small firms to large multi-national conglomerates
- Configurations are single standalone drives to fully integrated packages in a variety of applications
- Overall drive performance and reliability have been exceptional

M2LC — Reduced to Practice

- Agricultural Irrigation 93,000 acre potato farm in the Pacific Northwest
  - Massive and sophisticated irrigation system
- 4160V, 1500HP
- Installed/commissioned 03/15/13
- Operating experience
  - Experience to date has been very good
- Customer ordered a 2nd drive
  - 4160V, 1000HP
  - Installed and used extensively throughout the 2014 growing season

M2LC — Reduced to Practice

- Main line oil pumping application in Texas
- 4160V M2LC VFDs
  - 500HP and 900HP standalone
  - 2000HP and 3000HP with line synchronization packages energizing 2 and 3 and motors respectively
- All systems installed, commissioned and operating
- Largest pumping operation in Texas
  - 12,000 barrels of oil per hour

M2LC — Reduced to Practice

- Gas compression application
- Four 4160V, 5500HP VFDs with line synchronization packages
  - Inverters utilize 770A cells
- Liquid-cooled transformers located outdoors
  - Reduces heat load in equipment room
  - Lowered A/C costs
- Equipment installed and currently being commissioned

M2LC — Reduced to Practice

- Mining Application
  - Critical application to control airflow in mine
  - Must evacuate after 15 minutes if airflow stops
- 4160V, 1000HP
  - Runs 24/7
  - Remote communications via cellular modem
- Operating experience
  - Accumulated over 14,000 hours of continuous operation without incidents

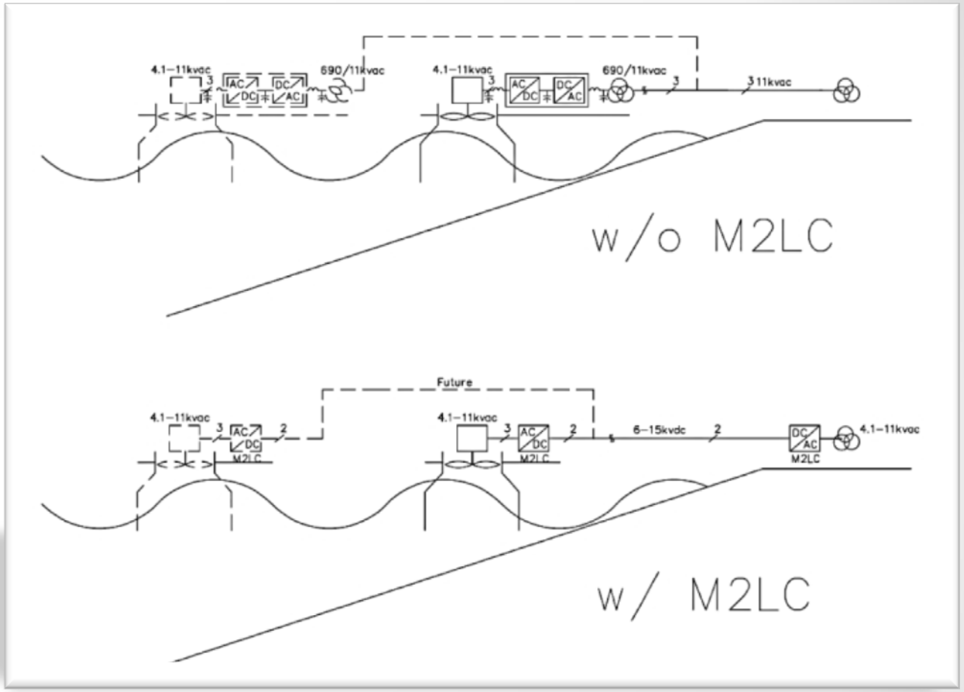
M2LC — Reduced to Practice

- Municipal Water Authority
- 4160V, 500HP
  - Remotely monitored
  - Customer noted significant reduction in energy consumption
- Operating experience
  - Experience to date has been very good
  - No incidents

Measured Efficiencies	
Converter	98.4%
Inverter	99.5%

Renewable Energy & Energy Sector

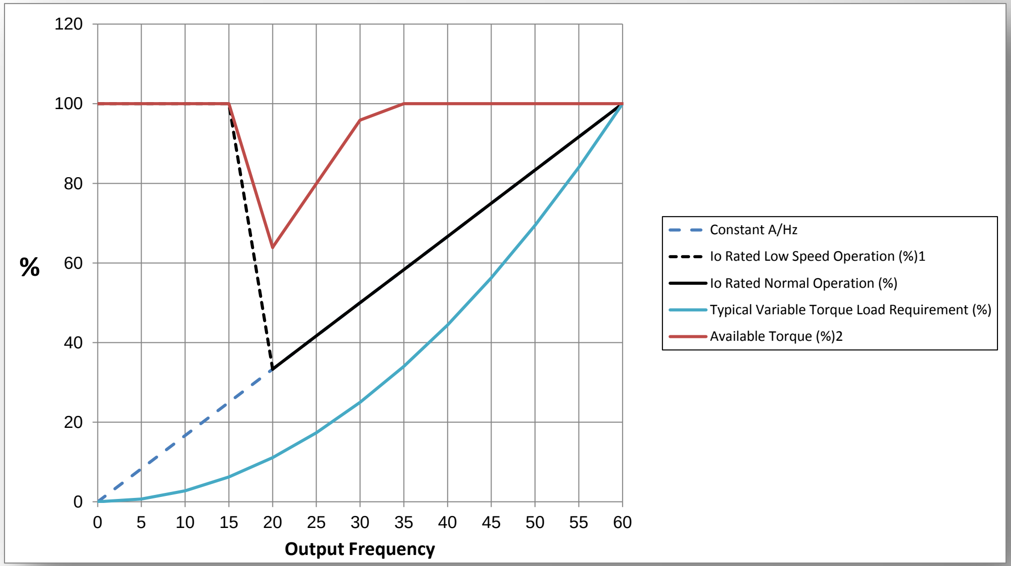
- In addition to motor control, design is also optimal for power transmission and generator power control applications for wind and tidal energy farms



- Significant weight reduction (eliminate filters and step-up transformer) and efficiency increase from being able to separate inverter using one large converter to collect power
- FACTS capabilities as a STACOM for utility-side interface

Challenges and Opportunities

- Gate phase shifting technique to cancel fundamental current in cell capacitors is very effective
  - Provides rated current for starting AC machines in variable torque applications
- Further opportunities to minimize voltage and current transients in arms during modulation change (typically between 20-25Hz)
- Currently 4th generation 1700v IGBT's and 1100v Film capacitors are optimal for M2LC MV mechanizations
- IGBT power and capacitor current densities are a fraction of competing designs
  - May significantly influence component design strategies in the future



IGBT Cost Analysis

	Vdc [1]	Normalized $/Usable KVA [2]
450A 1200v Dual	800.0	1.0
450A 1700v Dual	1100.0	1.0
400A 3300v Dual	1800.0	3.0
400A 6500v Single	3800.0	4.9

Existing Design
Note 1 Vdc is max usable voltage considering DC stability limit
Note 2 Usable KVA is Vdc/1.414 x Ic/1.414 of single IGBT

Film Capacitor Charge Density Comparison vrs Voltage

Rated Capacitor Voltage (v)	pu Volume Charge Density c-v/V [1]	pu cost per Coulomb $/c-v
700.00	1.17	1.16
900.00	1.29	1.06
1100.00	1.00	1.00
1300.00	0.83	1.20
1900.00	0.54	1.84
2500.00	0.37	2.94
3600.00	0.24	4.58
4000.00	0.21	4.96

References

- [1] L. Angquist, A. Antonopoulos D. Siemaszko, K. Ilves, M. Vasiladiotis, H-P Nee “Inner Control of Modular Multilevel Converters-An Approach using Open-loop Estimation of Stored Energy”, Laboratory of Electrical Machines and Power Electronics, Royal Institute of Technology, Stockholm, Sweden
- [2] A. Antonopoulos, L. Angquist, H-P Nee “On Dynamics and Voltage Control of the Modular Multilevel Converter”, Laboratory of Electrical Machines and Power Electronics, Royal Institute of Technology, Stockholm, Sweden
- [3] K. Ilves, A. Antonopoulos, S. Norrga, H-P Nee “A New Modulation Method for the Modular Multilevel Converter Allowing Fundamental Switching Frequency”, Royal Institute of Technology, Stockholm, Sweden
- [4] Patent US 8,618,698, B2 Issued US
- [5] Patent US2013/0234681 Pending
- [6] Patent WO 2012/018873 Approved US

Biographies of Presenters

<u>Marc F. Aiello - BS/MSEE P.E.</u>
37 years of product development experience in both power electronics and electro-optics with 17 patents granted or pending

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