Balanced Multiphase High Frequency Micro-Distribution Power Bus For Electric Vehicles (BM-HFMDB)

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***Abstract* - A Balanced Multiphase High-Frequency Micro-Distribution Bus (BM-HFMDB) for electric vehicles (EV) has the same copper (e.g., wire) utilization as the traditional DC bus but provides convenient compatibility with the major power consuming components of an EV, such as regenerative variable frequency AC electric motor or generator systems, but with fewer electronic stages for direct DC or AC conversion and without DC Link stages that always include bulky, inefficient, and expensive reactive components. Unlike all previously proposed multiphase high frequency distribution buses with replicated circuit topologies of simple isolated single phase or DC high frequency buses that were proven to be uneconomical, the BM-HFMDB economically and safely provides bi-directional multiphase power at any voltage, frequency and phase by appropriately modulating the power to the phase windings of a position-dependent-flux high frequency transformer (PDF-HFT) with simple choppers for sharing the common flux energy between phase windings.**

***Index Terms*— High frequency, Distribution Bus, High Frequency Distribution Bus**

I. INTRODUCTION

Electric Vehicles (EV) by nature have short electrical power distribution buses with many opportunities for voltage and frequency conversion along their path, such as high voltage variable frequency motors and generators, recharging systems, voltage matching accessories, power supplies, such as batteries, fuel cells, etc. In many cases, the power conversions are bi-directional to accommodate at least motoring and generating for propulsion and energy recovery, which always requires two electronic conditioning stages of conversion with one stage converting to an intermediate frequency, such DC from a battery, and a second stage converting from the intermediate frequency to the desired frequency and voltage of power transfer, such as DC, fixed and variable frequency single or multiphase AC. With advancements in fast electronic switching and high frequency accommodations, such as soft (e.g., resonant) switching to reduce at least switching loss, Litz wire to reduce transmission loss as a result of skin effect, and high frequency core materials to reduce transformer core loss, etc., an intermediate stage of high frequency is preferred because transformers and reactive components are more efficient, compact, and in many cases, less costly.

Since the major consumer of the EV distribution bus power is the electric propulsion system (e.g., the propulsion electric motor-generator), which always requires at least multiphase AC with variable frequencies on the order of the vehicle speed, this paper proposes a patented with patents pending Balanced Multiphase High Frequency Micro-Distribution Bus (BM-HFMDB) for electric vehicles (EV). With the BM-HFMDB itself serving as the intermediate frequency stage, any AC/DC power conversion point along the distribution bus is reduced to one simple modular bi-directional power stage with virtually the same circuit topology, such as compact a position-dependent-flux high frequency transformer (PDF-HFT) for controlled sharing of the common magnetic flux between phase windings to produce any power waveform without a DC Link Stage. Furthermore, the conversion module of the BM-HFMDB accommodates at least voltage translation, zero-crossing soft switching, simple and fast fault detection and breaking, while offering the same copper (e.g., wire) utilization as the DC bus but with more power converting compatibility with the major power consuming component of any EV, such as the electric motor or generator system.[1] In contrast, all previously proposed multiphase high frequency distribution buses are replications of simple isolated single phase or DC high frequency circuit topologies that have been proven to be uneconomical.[2]

II. COPPER UTILIZATION: DC VERSUS MULTIPHASE AC

There are three basic means for electricity distribution, Direct Current (DC), Single Phase Alternating Current (AC) and Multiphase AC with Three Phase AC (i.e., multiphase).

- DC power is the product of peak current and peak voltage = V_{PEAK} x I_{PEAK} or V*I, where V_{PEAK} is the maximum voltage and I_{PEAK} is the maximum current on the bus. Direct Current (DC) power distribution requires at least two conductors (i.e., neutral and live) to transfer V*I worth of power. The Normalized Power Transfer Per Conductor (NPTC), which is Power ÷ Number of Conductors, indicates the efficient use of conductors (e.g., copper utilization). For DC, the NPTC is 1/2 units per conductor.

- Single Phase AC power is the product of RMS current and RMS voltage = V_{RMS} x I_{RMS} or V*I/2, where VRMS is (Peak Phase Voltage $\div\sqrt{2}$) and I_{RMS} is (Peak Phase Current $\div\sqrt{2}$). Single Phase Alternating Current (AC) power distribution requires at least two conductors (i.e., neutral and live) to transfer V*I/2 worth of power. For

Single Phase AC, the NPTC is 1/4 units per conductor, which is ½ the utilization of copper as the DC bus.

- The power transfer for each phase (e.g., single phase) of Three Phase AC power is the product of RMS current and RMS voltage = V_{Peak} x I_{Peak}/2 or V*I/2. For all three phases, the Three Phase AC Power transfer is 3*V*I/2 or 1.5V*I. Three Phase AC power distribution requires at least three conductors to transfer 1.5V*I worth of power with an NPTC of 1/2 unit per conductor, which is the same as the normalized transfer per conductor for DC but twice the normalized transfer per conductor for Single Phase AC.

As shown, DC power and Three Phase AC power efficiently utilizes copper equally, which have half the copper utilization of Single Phase AC.

III. MULTIPHASE HIGH FREQUENCY DISTRIBUTION BUS

To reduce switching loss and to reduce the size and cost of the reactive components while improving efficiency, a high frequency power distribution bus should operate at the highest practical frequency that does not impose transmission line issues, such as skin effect, distributed impedance, and standing waves. It is commonly understood that the transmission line should be less than one-tenth of the quarter wave length to reduce transmission line effects with Litz wire mitigating the skin effect. Since the quarter-wave length of 24 kHz is less than one-thousands the average EV length of 3 meters, the impedance of a 24 kHz high frequency power EV distribution bus is simply lumped inductance and capacitance. With the inductance and capacitance per foot of a conductor in free space commonly understood to be about 70 nH and 30 pf, respectively, the 24 kHz, 3 meter EV power distribution bus shows a lumped inductance and capacitance of 0.70 μH and 300 pf, which are irrelevant to the average inductance of a 24 kHz high frequency transformer, which is about 11 mH, and a large 60 Hz electric motor or generator, which is about 740 mH. With current orthogonal to voltage, the inductive or capacitive impedances do not dissipate power but do change the power factor of the line, contribute to voltage drop along the line, and without proper shielding of the distribution conductor (e.g., coaxial cable, etc.), increase the radiation area, which provides a low resistive path to ground and a higher loss. But not possible with DC, lumped AC line inductance and capacitance can be conveniently leveraged in a resonant or soft switching application to provide a smoother and slower edge for switching the line power at the zero crossing points, which avoids destructive or dangerous standing waves, reduces switching loss, and reduces stress on the electronic switches. In addition, a high frequency power distribution bus can easily translate voltages with a compact electronic transformer.

IV. POWER CONVERSION BUILDING MODULE

Figure 1 shows the patented power conversion building module. In this example, a full bridge converter with bi-directional switches converts the DC or multiphase AC power (e.g., 3 phase AC) to a waveform with the multiphase AC enveloping a high frequency carrier, which drives the respective phase winding of a position-dependent-flux high frequency transformer (PDF-HFT). All switches are simple bi-directional AC choppers (e.g., back-to-back IGBTs) that are gated synchronously; hence, synchronous modulator-demodulator or Synchronous MODEM. Different from all other high frequency distribution buses with flux isolated phase windings (i.e., position-independent-flux high frequency transformer), all phase windings of the PDF-HFT are arranged to couple with a common magnetic flux path between each other; hence, a position dependent flux transformer, which is similar in electromagnetic operation to a wound-rotor doubly-fed electric machine, if the secondary of the PDF-HFT was allowed to move relative to the primary. As a result, any AC low frequency, including variable AC frequency, phase, and amplitude can be produced by sharing the common magnetic flux between all phase windings by appropriately modulating the Synchronous MODEMs of each phase with special compensated modulation techniques. As a result, the signals seen at the secondary terminal of the PDF-HFT are high frequency bipolar carrier signals with the envelope of the respective low frequency AC phase as a result of conditioning the modulation or gating of the synchronous MODEMS. Since the synchronous MODEMs produce bipolar high frequency carrier signals, inherent resonant (or zero-crossing soft) switching is easily accommodated. In addition, soft switching reduces stress on the components in the system, such as the electronic switches or reactive components, eliminates transmission line reflections, and can constructively utilize the impedance of any component in the system including the lump impedance of the power distribution bus, which may otherwise be considered parasitic. As shown, each phase distribution leg of the BM-HFMDB is connected to the respective secondary terminal of the PDF-HFT. A magnetizing current engine first establishes the pilot magnetizing current excitation, port voltages, and operating frequency (i.e., carrier frequency). A compensated modulation engine, which synchronizes to the carrier frquency, controls the modulation envelope and bi-directional power through the PDF-HFT by appropriately gating the synchronous MODEMs.

With the gating frequency synchronized between Power Conversion Building Modules (PCBM) of **Figure 1**, the

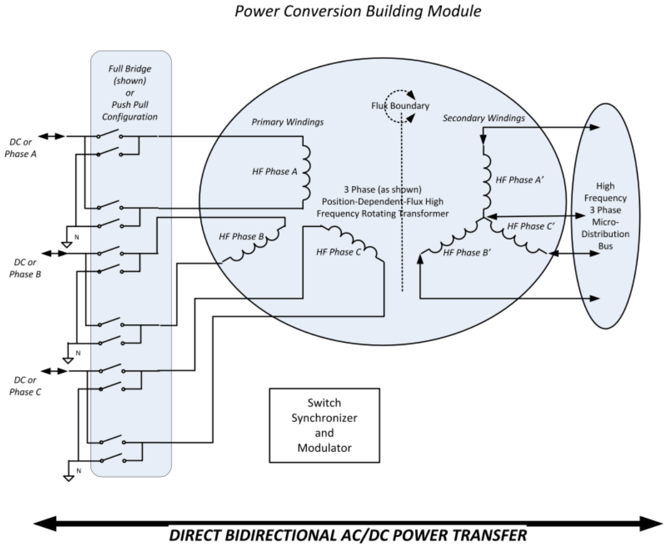

Figure 1

PCBM can be placed in paralleled or even in series for increased current or voltage (e.g., power stacking), respectively, or the PCBM can tap anywhere along the BM-HFMDB as shown in **Figure 2** for a complete symmetrical four quadrant AC/DC-to-AC/DC power system. For instance, one PCBM can supply variable frequency multiphase AC to the propulsion system (e.g., electric motor or generator) while another PCBM can be connected to a single or multiphase household power system for charging the battery through the BM-HFMDB. Although the PCBM is the basic building module, at least two PCBMs effectively form a conversion function. The chassis of the EV can be used as the neutral line to save the fourth conductor but by adjusting the gating in synchronism with the switching frequency, the balance between three phases can be maintained even with the neutral line removed. Furthermore, the BM-HFMDB can provide a satisfactory EV limp or failsafe mode with only 2 of the 3 phases of the power distribution bus operating, which is not possible with a failure of any line of the DC Distribution bus.

The back-to-back PCBMs require 24 bi-directional switches (e.g., 24 back-to-back IGBTs or 48 total IGBTs) for a 3-phase bi-directional full bridge circuit topology PCBM with direct AC/DC-to-AC/DC conversion, 8 junction drops of loss at the peak current and voltage (i.e., power) of an individual AC phase, and 50% duty cycle switching. Operating at the high chopping frequency, soft switching can be accomplished with reactive components limited to the junction capacitance of the switches and the lump impedances of the BM-HFMDB. In contrast, a conventional regeneration drive system for the 2010 Prius with a DC Link Stage requires 8 switches (i.e., IGBT) for a bi-directional 3-phase system at effectively 100% duty cycle with 3 junction drops of loss but at the peak-to-peak production power of the DC Link Stage, which is 3 times the power of an individual AC phase, and large reactive components (e.g., capacitors and chokes).[3] By reasonably assuming the cost of the semiconductor switch is directly proportional to the product of the rated power and operating duty cycle of the switch and the junction drop loss of the switch is directly proportional to the rated power of the switch, the switch cost factor of the PCBM is one-sixth (e.g., 1/3 * ½) the switch cost factor of the conventional system with a DC Link Bus and the switch loss factor of the PCBM is one one-third the switch loss factor of the conventional system. As a result, the normalized cost of the 8 switches of the conventional DC Link System (e.g., 8*6 = 48 switches) is equal to the normalized cost of the 48 PCBM switches but the 9 (e.g., 3*3 = 9) normalized junction drop loss of the switches of the conventional DC Link system is higher than the 8 normalized junction drop loss of the switches of the PCBM. The switch cost and loss analysis just presented does not consider the cost and loss of the large reactive components for the DC Link Stage of the conventional controller, which is substantial. Unlike the conventional controller, the PCBM inherently operates under resonant switching for substantial reduction in switching loss.

Figure 2 shows the BM-HFMDB always provides unidirectional or bi-directional power flow with one stage of power conditioning electronics for any module that reduces cost, increases efficiency and performance. With the BM-HFMDB as the intermediate stage, there is no DC link stage with large reactive components, such as chokes and capacitors, but instead, the PDF-HFT transformer, which is proportionally small and efficient with easy step-up or down voltages all in accordance with operating frequency. Furthermore, the modules circuit topology leverages the same circuit design, only adjusted for voltage (power).

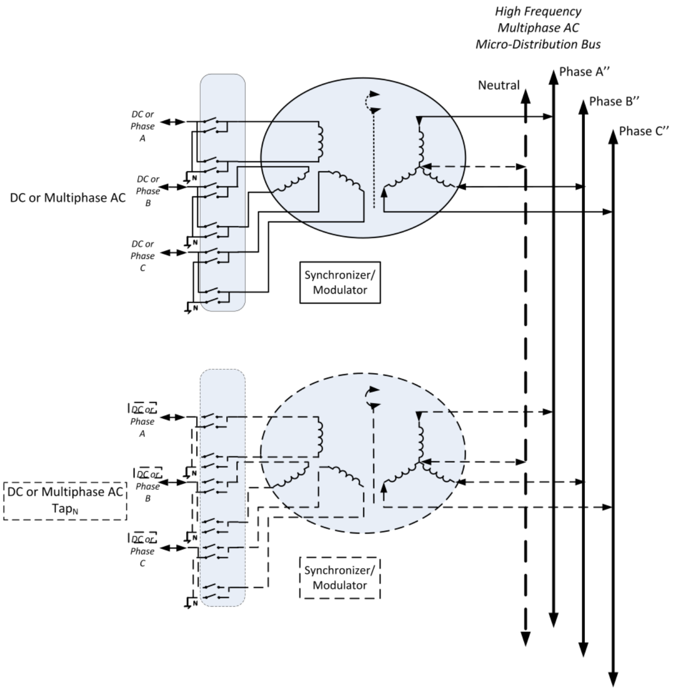

Figure 2

V. MULTIPHASE HIGH FREQUENCY DISTRIBUTION BUS FAULT

Upon detection of a distribution bus fault, such as a short, the power turn-off response should be performed as quickly as possible to avoid stressing electrical/electronic components. Electronic switches can switch within 1 us or better. For the BM-HFMDB, switching can be done at the zero crossing of voltage or current within the safe operating area of the electronic switch (20 us between zero crossings @ 25 kHz). This is not possible with a DC bus, which will always be switched at the highest voltage or current potential, which may cause distructive standing waves in the DC system.

VI. FLUX SHARING BETWEEN PDF-HFT PHASES

The BM-HFMDB is economical while providing of any frequency from DC to variable frequency AC by direct AC/DC-to-AC/DC conversion as only provided by sharing the common magnetic flux between the phase windings of a position-dependent-flux high frequency transformer (PDF-HFT) and gating of simple synchronous MODEMs.

A simple trigonometric analysis of modulating (i.e., beating) with three sinusoidal signals will show at least one method of power control of the PCBM. Let $Cos\ (Wt)$ represent the high frequency gate transition timing of the synchronous modem on one side of the PDF-HFT (e.g., primary side) and let $Cos\ (Wt + \varphi)$ represent the gate transition timing of the synchronous modem on other side of the PDF-HFT (e.g., secondary side). Both high frequency transition timings are out of phase by φ but synchronously operating at the same high frequency, W. Further, the resulting high frequency carrier signal (i.e., power signal) has a low frequency modulation envelope, $Cos\ (W_{60}t)$, due to the applied AC phase signal (e.g., 60 Hz) that is chopped by the high frequency, W. Using simple trigonometry, the following results from beating $Cos\ (Wt)$ with $Cos\ (Wt + \varphi)$ and again with $Cos\ (W_{60}t)$:

$$\begin{aligned} &Cos(W60t) \bullet \{Cos(Wt) \bullet Cos(Wt+\varphi)\} = \\ &Cos(W60t) \bullet \left\{ \tfrac{1}{2} \bullet [Cos(\varphi) - Cos(2Wt+\varphi)] \right\} \end{aligned} \tag{1}$$

The power signal (1) shows average power at 0 or 180 for φ (2):

$$\pm\, Cos(W_{60}t) \bullet \left\{ \frac{1}{2} \bullet [1 - Cos(2Wt)] \right\} \tag{2}$$

The power signal (1) show no average power or zero power at 90 or 270 degrees for φ (3):

$$\pm\, Cos(W_{60}t) \bullet \left\{ \frac{1}{2} \bullet Sin(2Wt) \right\} \tag{3}$$

At least by changing the offset timing, φ, of the gating between the synchronous modems on each side of the PDF-HFT the propagation of power can be varied. Since any fast transition periodic signal, such as a square wave, can be represented as a series (i.e., Fourier Series) of sinusoids with harmonics of the fundamental frequency, an AC chopped signal, such as the AC chopped signal resulting from gating the synchronous modems, would be represented by a Fourier series of $Cos\ (W_Nt)$ or $Cos\ (W_Nt + \varphi)$, where N represents frequency harmonic terms, with similar combinational results to the simple analysis just presented for $Cos\ (Wt)$ with $Cos\ (Wt + \varphi)$.

Another simple analysis will show how sharing of the magnetic energy between phases can change frequencies on each side of the PDF-HFT. Consider, W_x, and, φ_x, to be the frequency and phase, respectively, of the AC reference signals applied on one side of the PDF-HFT (e.g., primary side):

$$\begin{aligned} &Leg\_1 = Sin(W_xt + \varphi_{x1}); \\ &Leg\_2 = Sin\left(W_xt + \varphi_{x2} + \frac{2\pi}{3} \right); \\ &Leg\_3 = Sin\left(W_xt + \varphi_{x3} + \frac{4\pi}{3} \right); \end{aligned} \tag{4}$$

Where:

W_x = AC Electrical Frequency (e.g., 60 Hz);

$\varphi_{x1}, \varphi_{x2}, \varphi_{x3}$ = Adjustable phase angle of each phase.

Consider, W_y, and, φ_y, to be the desired frequency and phase of the signal on the other side of the PDF-HFT (e.g., secondary side). By modulating or beating the primary side signals of Leg_1, Leg_2, and Leg_3, respectively, with the following signals produced by controlling the high frequency gating of the synchronous MODEMs with compensated modulation:

Modulation for Leg_1:

$$ACos((W_x \pm W_y)t + \varphi_x \pm \varphi_{y1}); \tag{6}$$

Modulation for Leg_2:

$$ACos\left((W_x \pm W_y)t + \varphi_x \pm \varphi_{y2} + \frac{2\pi}{3} \right); \tag{7}$$

Modulation for Leg_3:

$$ACos\left((W_x \pm W_y)t + \varphi_x \pm \varphi_{y3} + \frac{4\pi}{3} \right); \tag{8}$$

Where:

$(W_yt + \varphi_y)$= Frequency and phase of the desired waveform;

$\varphi_{y1}, \varphi_{y2}, \varphi_{y3}$ = Adjustable phase angle of the desired waveform;

A = The adjustable amplitude (or multiplier), which includes the winding-turns ratio of the PDF-HFT;

± Direction of frequency (clockwise or counter-clockwise rotation on polar coordinates).

Note: As the waveform transitions become faster (such as a square wave), the relation is a Fourier series of harmonic components, which is a duplication of the proceeding relations for each term in the Fourier series.

Then considering only balanced phases (i.e., $\varphi_{x1} = \varphi_{x2} = \varphi_{x3}$) of the resulting signals for simplicity:

Leg_1':

$$\begin{aligned} &Leg\_1' = ACos((W_x \pm W_y)t + \varphi_x \pm \varphi_{y1}) \times Sin(W_xt + \varphi_x) \\ &+ ACos\left((W_x \pm W_y)t + \varphi_x \pm \varphi_{y2} + \frac{2\pi}{3} \right) \times Sin(W_xt + \varphi_x + \frac{2\pi}{3}) \\ &+ ACos\left((W_x \pm W_y)t + \varphi_x \pm \varphi_{y3} + \frac{4\pi}{3} \right) \times Sin(W_xt + \varphi_x + \frac{4\pi}{3}); \end{aligned} \tag{10}$$

Leg_1' relation can be further expanded:

$$
\begin{aligned}
Leg\_1' = {} & ACos\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_{y1}\right) \times Sin(W_x t + \varphi_x) \\
& + A\left[\begin{array}{l} Cos\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_{y2}\right)Cos\left(\dfrac{2\pi}{3}\right) \\ - Sin\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_{y2}\right)Sin\left(\dfrac{2\pi}{3}\right) \end{array}\right] \\
& \times\left[Sin(W_x t + \varphi_x)Cos\left(\frac{2\pi}{3}\right) + Cos(W_x t + \varphi_x)Sin\left(\frac{2\pi}{3}\right)\right] \\
& + A\left[\begin{array}{l} Cos\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_{y3}\right)Cos\left(\dfrac{4\pi}{3}\right) \\ - Sin\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_{y3}\right)Sin\left(\dfrac{4\pi}{3}\right) \end{array}\right] \\
& \times\left[Sin(W_x t + \varphi_x)Cos\left(\frac{4\pi}{3}\right) + Cos(W_x t + \varphi_x)Sin\left(\frac{4\pi}{3}\right)\right];
\end{aligned}
\qquad (11)
$$

On solution by reducing (11) and letting ($\varphi_{y1} = -\varphi_{y2} = \varphi_y$):

$$Leg\_1' = ACos\left(\left(W_x \pm W_y\right)t + \varphi_x \pm \varphi_y - (W_x t + \varphi_x)\right); \qquad (12)$$

And for simplicity, if ($\varphi_y = 0$) and ($\varphi_x = 0$), then Leg_1' becomes:

$$Leg\_1' = ACos\left(\pm W_y t\right); \qquad (13)$$

Purely a "real" component, (13) shows the desire waveform with a frequency, W_y, has been achieved by sharing the magnetic energy from the primary phase windings with a waveform of frequency W_x by modulating the synchronous modems with an additional frequency component of ($W_x \pm W_y$).

VII. PROPULSION EXAMPLE

Back-to-back PCBMs shown in **Figure 1** will effectively form the basis of brushless Real Time Control of electric machines (i.e., electric motors and generators), such as the brushless wound-rotor [synchronous] doubly-fed electric machine (BWRSDF) that is shown in **Figure 3**.[4] The BWRSDF effectively places two active stator assemblies (i.e., armatures) of equal rating (i.e., doubly-fed) into the same real-estate as a permanent magnet (PM) or induction electric machine by removing all rotor passive components, such as PM, squirrel cage windings, etc. and as a result, the BWRSDF effectively shows: 1) twice the power rating in the same size package as a permanent magnet (PM) or induction electric machine; 2) one half the electrical loss to power rating as a permanent magnet (PM) or induction electric machine; and 3) with the control electronics, which are virtually duplicate PCBMs, rated to one-half the power rating of the electric machine. In contrast, a PM or Induction electric machine (i.e., singly-fed) of the same loss and size but half the power rating would incorporate one PCBM.

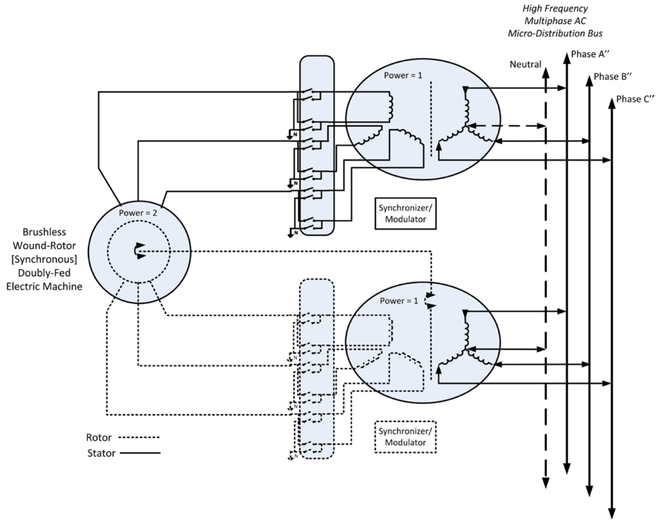

Figure 3

VIII. CONCLUSION

With the same power carrying capacity, the same efficiency, and the same copper utilization, the BM-HFMDB can easily compete with the DC power distribution bus economically but as a support system, the BM-HFMDB universally uses fewer electronic conversion stages and accommodates stress-less soft-switching while providing failsafe and fault tolerant operation, which shows another level of improvement in cost, efficiency, and size. Each electronic stage or PCBM can tap the BM-HFMDB anywhere along its path to conveniently power an EV accessory with DC, single or multiphase AC of any power. Without a DC Link Stage and its bulky, lossy, and expensive reactive components, the same modular circuit topology of any PCBM includes a compact position dependent flux, high frequency transformer (PDF-HFT), which can provide virtually any power waveform by controlling simple synchronous MODEMs (e.g., AC choppers) to share the common magnetic flux between phase windings.

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