Solid State Transformer (SST) With a Position Dependent Flux High Frequency Transformer (PDF-HFT) For Magnetic Flux Sharing Instead of a DC Link Stage with Electric Field Sharing (Sept 2016)

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Abstract— **The patented Brushless Multiphase Self-Commutation Controller (BMSCC) is effectively a bi-directional Solid State Transformer (SST) that uniquely comprises a compact and efficient Position Dependent Flux Multiphase High Frequency Transformer (PDF-HFT) circuit topology and special modulation techniques to implement magnetic flux sharing between phase coils of the PDF-HFT. As a result, BMSCC directly translate nearly pure DC or multiphase AC waveforms of any frequency or phase to another DC or multiphase AC waveforms of any frequency or phase without a DC Link Stage that uses large reactive components, such as bulky capacitors, for implementing electric field energy sharing.**

***Index Terms*—Brushless, wound rotor, doubly fed, double fed, synchronous, asynchronous, electric machine, electric motor, electric generator, electric propulsion**

I. Introduction

Global electricity consumption is expected to continually grow faster than the 47% growth already experienced from 2000 to 2012 [1]. In 2015, the World Economic Forum reported the need for a transformational investment of more than $7.6 trillion over the next 25 years (or $300 billion per year) to modernize, expand, and decentralize the electricity infrastructure for at least: 1) continuing the global growth of electricity production from renewable energies; 2) reducing global emissions; and 3) sustaining global economic growth [2]. In the report's conclusion, technical innovation is the enabling key for realizing the transformation. As a basic circuit topology for Motor Controllers, Frequency Changers, Power Factor Correctors, etc., the Solid State Transformers (SST) as only the patented Brushless Multiphase Self-Commutation Controller (BMSCC) provides is the enabling key.

The patented Brushless Multiphase Self-Commutation Controller (BMSCC) is effectively a bi-directional Solid State Transformer (SST) that unique comprises a compact and efficient Position Dependent Flux Multiphase High Frequency Transformer (PDF-HFT) circuit topology and special modulation techniques to implement magnetic flux (or energy) sharing between phase coils of the PDF-HFT. As a result, BMSCC directly translate nearly pure DC or multiphase AC waveforms of any frequency or phase to another DC or multiphase AC waveforms of any frequency or phase without a DC Link Stage with large reactive components, such as bulky capacitors, for implementing electric field energy sharing. To name a few important Smart Grid technologies, the robust modular circuit topology of BMSCC provides: 1) a compact and low cost utility SST of any power rating; 2) the patented Brushless Real Time Emulation Controller (BRTEC) for implementing the only practical brushless and fully stable wound-rotor synchronous doubly fed electric machine system, such as Synchro-Sym, which without the invention of BRTEC, experts could only hypothesize as early as 1960 to show impressive attributes of highest efficiency, lowest cost, and highest torque/power density of all other electric machines; 3) frequency changers; 4) power factor correctors; and 5) Synchro-Phasors [3]. In addition, the robust modular circuit topology of BMSCC inherently accommodates the elevated temperature levels of Wide Bandgap Semiconductor, resonant (or soft) switching, multilevel voltage translation, bidirectional, rapid fault protection at zero crossing to avoid the effects of standing waves, high frequency multiphase micro-distribution buses for electric vehicles, and so on.

Figure 1 shows one possible circuit topology of the modular Brushless Multiphase Self Commutation Controller (BMSCC) that comprises at least a two-phase Position Dependent Flux High Frequency Transformer (PDF-HFT) and Synchronous Modulator-Demodulators (SMODEM) driving each phase winding of the PDF-HFT, which place the envelope of the phase signals, such as $Phase_{as}$, $Phase_{bs}$, $Phase_{ar}$, and $Phase_{br}$, over the switching frequency (or carrier signal) of the SMODEM. A two phase PDF-HFT was chosen instead of a three or more phase PDF-HFT to greatly simplify the operational relationships presented. For this example, each SMODEM is effectively a full AC bridge arrangement of four AC switches, S1-S4, to provide bi-directional propagation of DC or AC power from the primary to secondary side of the PDF-HFT. But any circuit that satisfactorily modulates the PDF-HFT AC phases with bipolar high frequency signals could be used, such as a Push-Pull Bridge of AC switches. As shown, the primary and secondary sides of the two-phase PDF-HFT comprise balanced arrangements of two phase windings, which are oriented at 90 degrees. Similarly, the phase windings

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of a balanced 3 phase arrangement would be 120 degrees apart, and etc. The magnetic flux coupling between the balanced phase windings of the primary and secondary sides of the PDF-HFT is dependent on the phase angle, θ, which can be fixed at any angle or varied with articulation between the primary and secondary sides. All AC switches of the SMODEM (S1-S4) effectively provide a full bridge chopper synchronized with the carrier of the modulation, which is based on the high frequency design of the PDF-HFT. There are several circuit configurations for an AC switch, such as two IGBTs with flyback diodes in an emitter to emitter connection arrangement. For satisfactory operation, other components of the BMSCC circuit topology may be included, such as small capacitors in parallel with the junction capacitance of switches, S1-S4, placed in series with the leakage inductance of the PDF-HFT to implement resonant (or soft) switching. Noticeably, BMSCC comprises no intermediate DC Link Stage with dual stages of electronics and temperature sensitive large reactive components, such as capacitors, and as a result, BMSCC conveniently accommodates the efficiency improvements, the temperature elevation, and the cost and bulk reduction of wide bandgap semiconductors, such as with silicon carbide substrate (SiC).

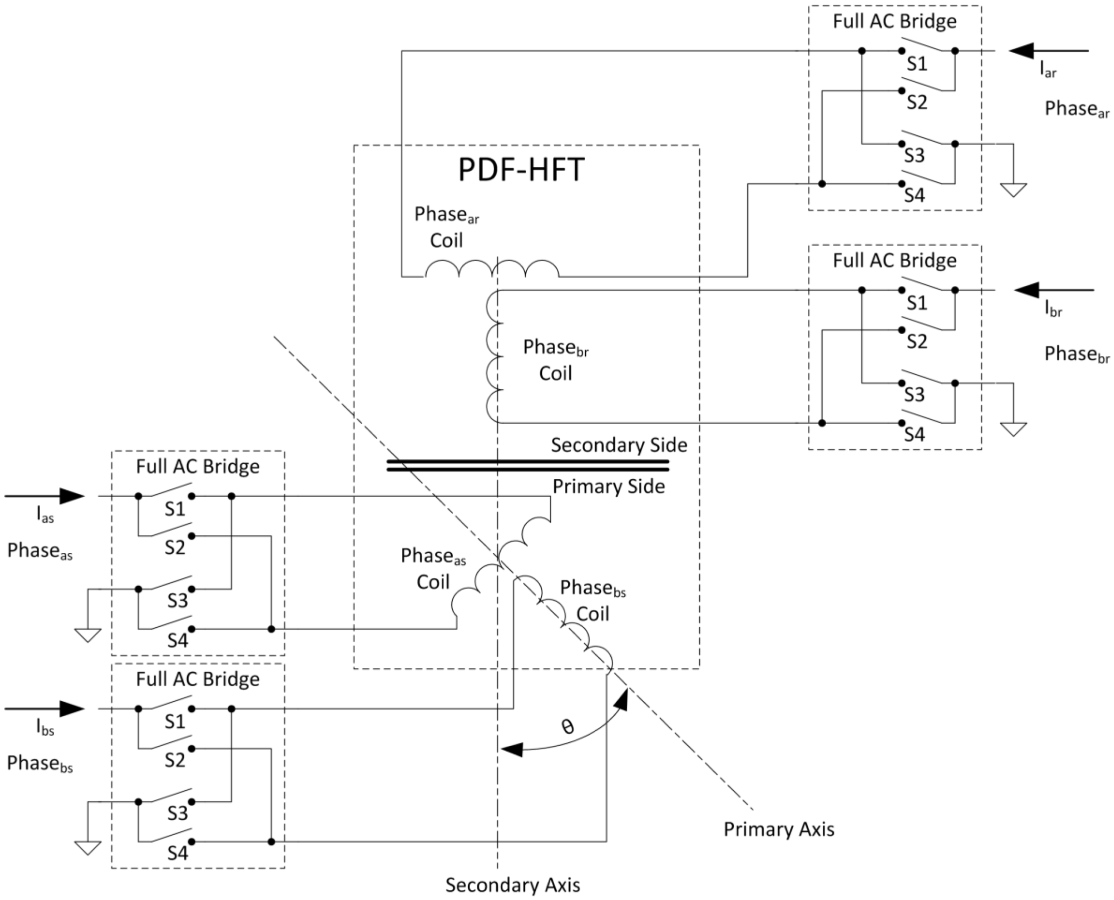

Figure 1

By judiciously modulating the SMODEMs, frequency and phase conversion between the primary and secondary AC port signals is provided by sharing magnetic flux (or energy) between phases of the PDF-HFT instead of traditionally sharing electric field energy from the capacitor bank of a DC Link Stage. The mechanical angle relationship between the primary and secondary of the PDF-HFT is $\theta = W_{Me}t + \gamma$, where, θ is the mechanical angle between the secondary and primary axis, t is time, W_{Me} is mechanical angular velocity, γ is the instantaneous phase angle between the primary and secondary winding sets. Let the currents applied at the phase ports, Phase$_{as}$, Phase$_{bs}$, Phase$_{ar}$, and Phase$_{br}$ be $I_{as} = I_s Cos(W_s t + \beta)$, $I_{bs} = I_s Sin(W_s t + \beta)$, $I_{ar} = I_r Cos(W_r t + \sigma)$, and $I_{br} = I_r Sin(W_r t + \sigma)$, where σ and β are arbitrary phase angles of the secondary and primary currents, respectively, W_r is the frequency of the AC phase waveforms on the secondary side, and W_s is the frequency of the AC phase waveforms on the primary side. Understand, W_r and W_s become components of the modulation envelopes with the high frequency carrier frequency provided by the SMODEMs. The SMODEMs also provide another selectable component of the modulations envelopes, $ASin((W_s \pm W_r)t + \varphi_x \pm \varphi_{y1})$ and $ACos((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2})$, respectively, for at least the AC phases I_{as} and I_{bs}, where A is the selectable modulation amplitude. Using simple trigonometry for the flux coupling between phase windings but for simplicity modulating with no frequency or phase component for $ASin((W_s \pm W_r)t + \varphi_x \pm \varphi_{y1})$

and $ACos((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2})$, the magnetic flux relationships for each of the four balanced phase windings are:

$$\lambda_{as} = AL_sI_{as} + AMI_{ar}Cos(\theta) + AMI_{br}Cos(\theta+90) = AL_sI_{as} + AMI_{ar}Cos\theta - AMI_{br}Sin\theta; \quad (1)$$

$$\lambda_{bs} = AL_sI_{bs} + AMI_{ar}Cos(90-\theta) + AMI_{br}Cos(\theta) = AL_sI_{bs} + AMI_{ar}Sin\theta + AMI_{br}Cos\theta; \quad (2)$$

$$\lambda_{ar} = AL_rI_{ar} + AMI_{as}Cos(-\theta) + AMI_{bs}Cos(90-\theta) = AL_rI_{ar} + AMI_{as}Cos\theta + AMI_{bs}Sin\theta; \quad (3)$$

$$\lambda_{br} = AL_rI_{br} + AMI_{as}Cos(-\theta-90) + AMI_{bs}Cos(-\theta) = AL_rI_{br} - AMI_{as}Sin\theta + AMI_{bs}Cos\theta; \quad (4)$$

where $M = N_sN_rL_m$ is the transformer or coupled mutual inductance, $L_s = N_sN_sL_l$ and $L_r = N_rN_rL_l$ are the primary and secondary self-inductance do to leakage (or non-coupled) inductance, N_r is the number of winding-turns on the secondary, N_s is the number of winding-turns on the primary, Ll is the permeance of the leakage (uncoupled) magnetic circuit path not contained by the magnetic core, Lm is the permeance of the coupled magnetic circuit path contained by the magnetic core. Since the leakage path is generally outside the core and closer to the permeability of air, $Lm >> Ll$ or $M >> L_r$ or L_s. Further expansion of (1), (2), (3), (4) with the substitution of the port currents under modulation:

$$\lambda_{as} = AL_sI_sCos(W_st+\beta) + AMI_rCos(W_rt+\sigma)*Cos(W_{Me}t+\gamma) - AMI_rSin(W_rt+\sigma)*Sin(W_{Me}t+\gamma); \quad (5)$$

$$\lambda_{bs} = AL_sI_sSin(W_st+\beta) + AMI_rCos(W_rt+\sigma)*Sin(W_{Me}t+\gamma) + AMI_rSin(W_rt+\sigma)*Cos(W_{Me}t+\gamma); \quad (6)$$

$$\lambda_{ar} = AL_rI_rCos(W_rt+\sigma) + AMI_sCos(W_st+\beta)*Cos(W_{Me}t+\gamma) + AMI_sSin(W_st+\beta)*Sin(W_{Me}t+\gamma); \quad (7)$$

$$\lambda_{br} = AL_rI_rSin(W_rt+\sigma) - AMI_sCos(W_st+\beta)*Sin(W_{Me}t+\gamma) + AMI_sSin(W_st+\beta)*Cos(W_{Me}t+\gamma); \quad (8)$$

Further reduction of the magnetic flux relations ((5), (6), (7),(8)) with ($\pm W_r = \pm W_s \pm W_{Me}$), which is the synchronous speed relation:

$$\lambda_{as} = AL_sI_sCos(W_st+\beta) + AMI_rCos(W_st+\gamma+\sigma); \quad (9)$$

$$\lambda_{bs} = AL_sI_sSin(W_st+\beta) + AMI_rSin(W_st+\gamma+\sigma); \quad (10)$$

$$\lambda_{ar} = AL_rI_rCos(W_rt+\sigma) + AMI_sCos(W_rt-\gamma+\beta); \quad (11)$$

$$\lambda_{br} = AL_rI_rSin(W_rt+\sigma) + AMI_sSin(W_rt-\gamma+\beta); \quad (12)$$

$$Voltage = -d\lambda/dt; \quad (13)$$

$$V_{as} = -AL_sI_sSin(W_st+\beta) - AMI_rSin(W_st+\gamma+\sigma); \quad (14)$$

$$V_{bs} = AL_sI_sCos(W_st+\beta) + AMI_rCos(W_st+\gamma+\sigma); \quad (15)$$

$$V_{ar} = -AL_rI_rSin(W_rt+\sigma) - AMI_sSin(W_rt-\gamma+\beta); \quad (16)$$

$$V_{br} = AL_rI_rCos(W_rt+\sigma) + AMI_sCos(W_rt-\gamma+\beta); \quad (17)$$

Although simple sinusoidal waveforms were used for ((9), (10), (11), (12) and (14),(15),(16),(17)), any periodic waveform, such as the complex and edgy high frequency modulated waveforms, can be constructed and analyzed by superposition of the appropriate Fourier Series of sinusoidal waveforms and therefore, would show the same result per term.

As in any transformer, the PDF-HFT self (or leakage) inductances, L_r and L_s, which are non-linear functions of the low permeance non-coupled inductance and as a result, much smaller than the high permeance mutual inductance, should be kept to a minimum. However with at least the junction capacitance of the switches, S1…S4, in series with the self-inductance circuit path, resonant (or soft) switching with the appropriate switching frequency alleviates the parasitic effects of self-inductance while confining the resonating circulating currents to the high frequency side of the SMODEMs and PDF-HFT and away from the low frequency port signals. By switching at zero crossings, switching loss and stress are also reduced. The patented BMSCC comprises an integral Magnetizing Current Generator (MCG) component for at least the purpose of strategically providing resonant switching and as a result with $M >> L_r$ or L_s, the non-linear self-induction terms can be neglected with (9), (10), (11), (12) and (14),(15),(16),(17) reducing to:

$$\lambda_{as} = AMI_rCos(W_st+\gamma+\sigma);$$

Or

$$V_{as} = -AMI_rSin(W_st+\gamma+\sigma); \quad (18)$$

$$\lambda_{bs} = AMI_rSin(W_st+\gamma+\sigma);$$

or

$$V_{bs} = AMI_rCos(W_st+\gamma+\sigma); \quad (19)$$

$$\lambda_{ar} = AMI_sCos(W_rt-\gamma+\beta);$$

or

$$V_{ar} = -AMI_sSin(W_rt-\gamma+\beta); \quad (20)$$

$$\lambda_{br} = AMI_sSin(W_rt-\gamma+\beta);$$

or

$$V_{br} = +AMI_sCos(W_rt-\gamma+\beta); \quad (21)$$

Instead of sharing the magnetic energy between phases of a PDF-HFT by relative rotation between the primary and secondary windings, similar effect is accomplished by synchronously modulating and demodulating each of the primary and secondary phase signals (see expansion of (1), (2), (3), (4), λ_{ar}) with the appropriate mix of $ASin((W_s \pm W_r)t + \varphi_x \pm \varphi_{y1})$ and $ACos((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2})$. By enabling the frequency and phase $((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2})$ of the modulation of I_{as} and I_{bs} with θ fixed at $\pi/4$ for equally sharing magnetic energy between all phase coils for analysis simplicity, then:

$$\lambda_{ar} = ACos((W_s \pm W_r)t + \varphi_x \pm \varphi_{y1}) \times I_sMCos(W_st+\beta) + ASin((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2}) \times I_sMSin(W_st+\beta); \quad (22)$$

Letting ($\varphi_{y1} = -\varphi_{y2} = \varphi_y$), which is analogous to driving with inverted sides of the SMODEMs, the solution is $\lambda_{ar} = AI_sMCos((W_s \pm W_r)t + \varphi_x \pm \varphi_y - (W_st+\beta))$ or $\lambda_{ar} = AI_sMCos(\pm W_rt \pm \varphi_y)$ with ($\varphi_y = 0$) and ($\varphi_x = \beta$), which is the same results as (20). Similar results for all phases of the PDF-HFT follow. As a result, the PDF-HFT propagates and balances any leading, lagging, or unity multiphase power between the primary and secondary winding sets across a single magnetic interface plane (e.g., air-gap) by modulated magnetic sharing between phases.

The PDF-HFT may include a small air-gap for even distribution of the flux, to avoid saturation, to allow angular adjustment between the primary and secondary, and to provide additional leakage inductance to accommodate resonant switching. Internal studies show the split core, axial-flux form of the PDF-HFT satisfies these requirements while providing an easy outside-inside automated winding approach and accommodating amorphous metal ribbon construction for satisfactory high power, high frequency operation. A Laminated Object Manufacturing (LOM) 3D Printer for electric machines, called MotorPrinter, was patented for at least the rapid manufacture of axial flux PDF-HFT cores with integral frame and performance material.

CONCLUSION:

Instead of sharing the electric field energy from bulky, expensive, and inefficient capacitor banks of a DC Link Stage, (18), (19), (20), (21) show the phase and frequency of the primary signals, $I_{as} = I_s Cos(W_s t + \beta)$ and $I_{bs} = I_s Sin(W_s t + \beta)$, can be automatically and purely matched to the phase and frequency of the secondary signals, $I_{ar} = I_r Cos(W_r t + \sigma)$ and $I_{br} = I_r Sin(W_r t + \sigma)$, without extraordinary filtering but by uniquely sharing the magnetic flux energy between phases of a compact and efficient PDF-HFT, such as by angular rotation (or moving) between the primary and secondary of the PDF-HFT or by synchronously modulating-demodulating the primary and secondary signals with $ASin((W_s \pm W_r)t + \varphi_x \pm \varphi_{y1})$ and $ACos((W_s \pm W_r)t + \varphi_x \pm \varphi_{y2})$ as only provided in conjunction with a MCG. As a result, BMSCC directly translate DC or multiphase AC waveforms of any frequency or phase to another nearly pure DC or multiphase AC waveforms of any frequency or phase. Providing automatic tracking by rotational connection, BMSCC implements brushless real time emulation control (BRTEC) that experts have hypothesized since at least 1960 to provide the only means for a truly brushless and fully stable wound-rotor synchronous doubly-fed electric machine system, such as Synchro-Sym. In addition, BMSCC provides the modular building blocks for frequency changers, power factor correctors, a multiphase Micro-Distribution Bus for electric vehicles, and so on [4].

A. Accurately Consistent EMS Terminology

The rapid advancement in high performance materials and brushless real time emulation control (BRTEC)

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