

# Homopolar Electro-mechanical Rotary Power Converter (HERPC)

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**Abstract** — A Homopolar Electro-mechanical Rotary Power Converter is proposed that has an application in High Voltage Direct Current (HVDC) power distribution systems and also industrially sized three-phase systems fuelled by DC producing renewable energy sources. The HERPC employs a homopolar rotor that carries no windings, power only being supplied by an external drive to overcome mechanical losses. The HERPC requires neither slip rings nor a brush type commutator.

## I. INTRODUCTION

Edison in the late 1870s first established the electric power business. Power was generated and distributed as DC, because then only DC motors existed. Very soon however, Westinghouse employed Stanley, who in 1886 developed an effective transformer. Later, in 1888 Westinghouse purchased the patents for Tesla's Alternating Current (AC) induction motor. By 1890 the Westinghouse Company was installing substantial high voltage AC transmission systems feeding lower voltage distribution systems. Until 1920, the AC and DC systems were largely competitive due to the rotary converter. The converter was able to generate DC from AC and consequently drive the commonplace DC motors. Demands for higher power levels and longer circuits however required higher voltages. Eventually DC power systems were constrained by the voltage factor. The AC systems due to the transformer, could apply the higher voltages with ease. This led to the dominance of AC over DC. DC however is now emerging as an effective and sometimes superior power transmission alternative. The resurgence of HVDC started in the 1930s and 40s when during World War II the Germans developed plans to implement an HVDC link using electronic mercury arc valves. These were to be configured as AC to DC and DC to AC power converters. The war however prevented its implementation. After the war in 1950, the Russians adopted the plans and built a successful 120kV, 65 mile long line from Moscow. From that initial scheme, HVDC power transmission has developed via power electronics through mercury arc valves, to semiconductor thyristors and latterly transistors. Now many of the world's largest power transmission schemes apply HVDC.

As power and distance limits have increased over the years, it is the turn of AC transmission schemes to be constrained. Excessive currents due to line charging and line voltage instability set power transfer limits, especially in cable systems. Power companies have consequently been turning to HVDC transmission.

To operate, a modern HVDC Power Electronic Converter (PEC), in the rectifier mode, breaks up the AC waveform and reconstructs it into DC. It does the same in

the inverter mode from DC to AC. The disarrangement – rearrangement however is not straight process reversal between the rectifier and inverter. The resulting pieced together waveforms are imperfect and contain harmonics. Energy losses occur due to conduction and switching in the semiconductor devices. Large power Voltage Source Converters (VSCs) are claimed to be about 96.5% efficient. Reduction of the harmonics is possible by filtering, however energy losses are then also incurred in the filters. The overall amount of equipment required is substantial and costly. Because of their complexity and size, HVDC PECs are generally air insulated. The converter chambers contain exposed live parts and staff must follow special procedures when working within their vicinity.

An alternative to the PEC is the Electro-mechanical Rotary Power Converter. Prior art for the ERPC has arisen mainly in the aircraft industry [1] in which multipolar devices have been used as power devices at 400Hz. The number of poles and winding arrangement that these devices employ however restrict their suitability for 'Utility' sized machines.

This paper describes a new form of ERPC, namely the (Homopolar) HERPC. The HERPC, if implemented would have many advantages over the incumbent PEC. It would be substantially safer by not having exposed live parts; be relatively small and compact consisting only of a small number of assembled parts; be easy to manufacture due to its rotating machine construction; be extremely reliable, similar to that of an AC motor; and have a high efficiency. As an inverter it would develop near perfect AC waveforms.

The applications for the HERPC are numerous. It is scalable to operate with very high power transmission systems or industrially sized three-phase systems fuelled by renewable energy sources. It has particular advantages for the offshore industry where 'Power from Land' schemes are beginning to be applied [2], primarily for safety and environmental reasons.

## II. PRINCIPLE OF OPERATION

The Figures shown are of a conceptual nature. They illustrate the principle of operation and features that need be applied in the device's construction.

Figure 1 shows the basic arrangement for the HERPC. Each one of the three-phase AC windings has coils that encircle each stator limb that bears a pole, in the respective phase set.

A principal winding has coils that encircle all the stator limbs that bear poles, on all the phase sets.

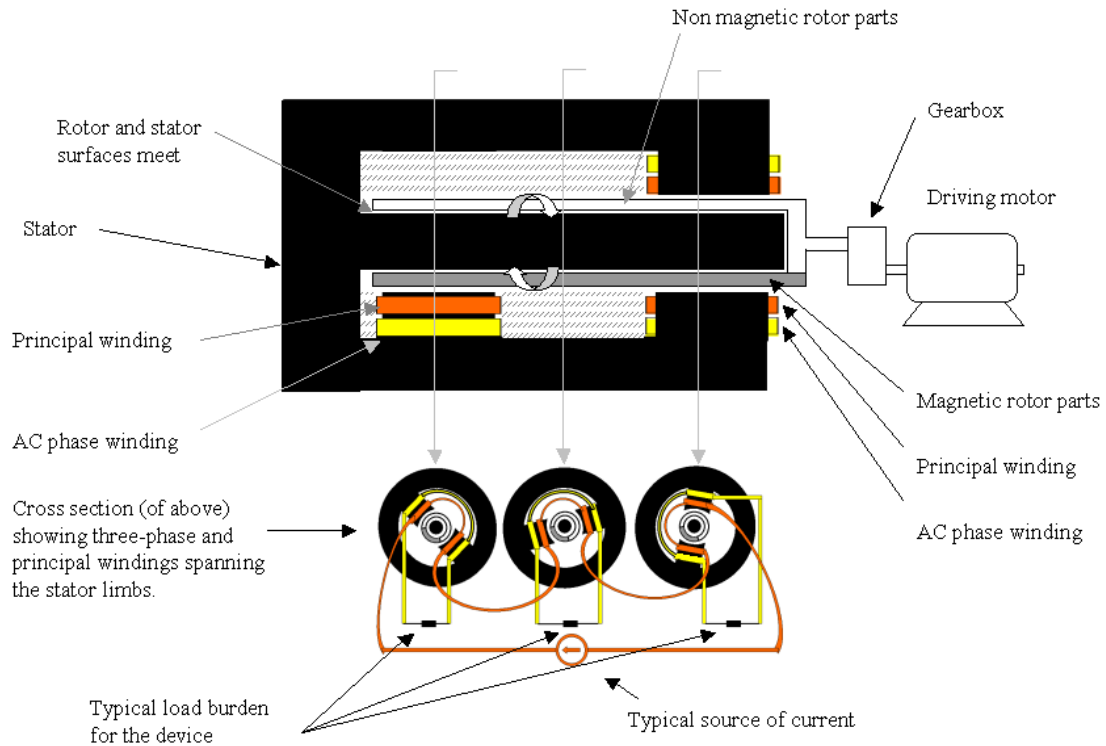


Figure 1. Basic arrangement for HERPC

Conversion from DC, to three-phase AC is a result of the variable reluctance of the three-phase sections of the magnetic circuit, developed by driving the rotor externally.

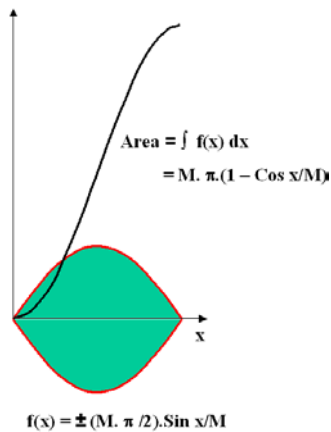


Figure 2. Function of stator AC winding limb face

The rotor carries no windings. This is a particular advantage over wound rotor machines in which joule heating and centrifugal force effects lead to restrictive designs. The function of the rotor is to divert the magnetic flux on a time varying basis through each of the three-phase windings. It consists of some magnetically conducting portions, and some nonmagnetically conducting portions. The nonmagnetic portions are required to channel the flux and prevent magnetic short circuits. An auxiliary motor drives the rotor at the

appropriate speed to generate the desired output AC frequency.

The shape of the AC winding pole faces determines the shape of the output AC waveforms. The induced AC voltage is proportional to the rate of change of flux passing through the winding. The flux however is distributed in proportion to the reluctance of the magnetic circuits - which is in turn proportional to the overlapping areas between the passing rotor and stator poles.

The shape of the stator pole faces corresponds to the difference between a positive and negative sinusoid. Figure 2 shows the shape and the area functions for the overlapping faces.

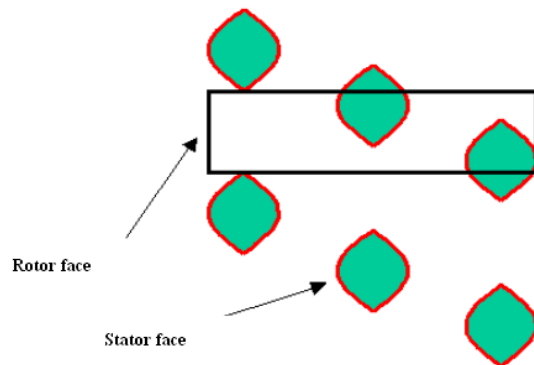


Figure 3. Progression of rotor across stator limb faces

Figure 3 shows the overlap at one angular position of the rotor. By taking this through a complete revolution, it may be seen how the overlapping area on each phase changes in a sinusoidal pattern. At any one time, the

reluctance of the parallel combination of all the limbs is constant.

When operating as an inverter, the phasor relationship of the flux, is shown in Figure 4.

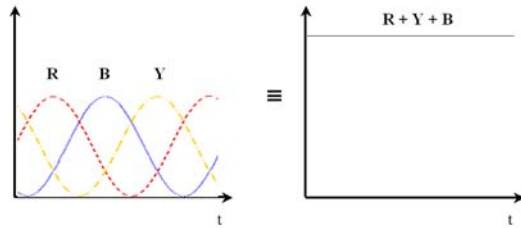


Figure 4. Phasors during inverter operation

The phasor addition of the three individual phases is a value at one-and-a-half times the peak-to-peak phase amplitude and corresponds to the flux developed by the DC excitation. A mathematical treatment is given in the appendix.

When unloaded, electro motive forces (emfs) appear on the output windings as a result of the magnetizing flux and Faraday's law ( $e = +N \cdot d\Phi_m/dt$ ). When loaded, the output currents produce voltages across the load burden via the AC windings. The output voltages are determined by the sum of the forward and back emfs. The back emfs obey Lenz's law ( $e_b = -N \cdot d\Phi_{dm}/dt$ ) and produce a de-magnetizing flux. The overall flux is the sum of the magnetizing and de-magnetizing fluxes.

In any circuit Ampere's law must be obeyed (i.e.  $I = \oint H \cdot dl$ ). Over the limbs encircled by the principal winding, if the input current is a constant then so must be sum of the magnetic fields (H) and consequently the sum of the fluxes.

Because the de-magnetizing flux attempts to reduce the overall flux, the source flux must increase to compensate. The de-magnetizing flux may be regarded as a back emf affecting the source. The input voltage is forced to increase to overcome the back emf. When the device is current driven it is therefore characterized by the input voltage following the load.

The magnetic circuits are arranged such that the flux links through windings rather than cutting across conductors. The Lorentz force law ( $F=B \cdot I \cdot L$ ) that applies to generators is therefore minimal. Restraining forces on the rotor are mainly those due to friction and windage.

Figure 1 shows two AC coils per phase. As the rotor turns through one complete rotation, one frequency cycle of flux passes through each of the coils. The two coils are therefore connected in series resulting in two cycles of output current per revolution of the rotor.

The arrangement of Figure 1 is conceptual. It is presented for ease of explanation. Other arrangements are also possible.

As with other AC machines, the AC portions of the magnetic circuit will be laminated. Laminations however may also be required on some parts of the DC magnetic circuit where the flux rotates relative to the material. If the magnetic material used is electrically conductive, then

eddy currents will arise. Suitably designed laminations will reduce the effect.

The HERPC is particularly applicable to HV systems because of the simplicity and arrangement of the windings which may be readily wound using conventional HV transformer techniques, or using the more recent approach [3], of winding with conventional power cables.

### III. PERFORMANCE

Figure 5 shows the device fed by a conventional thyristor rectifier bridge and DC line reactor. The HERPC is therefore acting as a direct replacement of the thyristor inverter bridge in a classic HVDC distribution system.

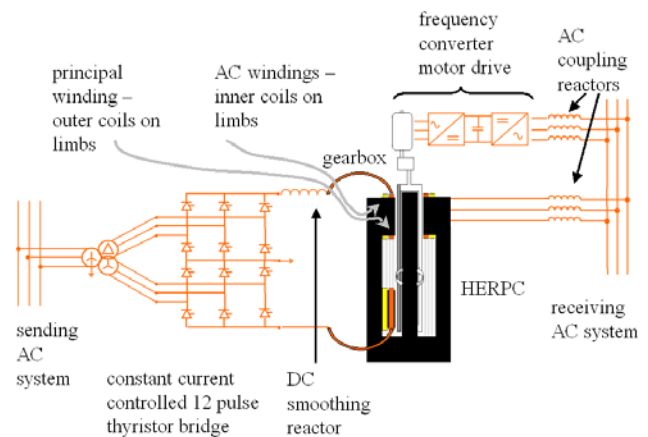


Figure 5. AC to DC to AC power distribution configuration

The equations in the appendix, and the associated calculations, predict (without optimization) that a 40MVA machine including auxiliaries could be installed in a volume approximately 10m in length with a cross section 4m high by 4m wide. An approximate weight is 100 tonne. By comparison, an estimate for the recently announced [4] 40MVA PEC is 16m in length, with a cross section 16m high and 10.5m wide, and a weight of 250 tonne.

The calculations show that a powerful motor is required to accelerate the rotor to the desired speed within a reasonable time. The recently developed 5MW, 230 rpm, High Temperature Superconducting (HTS) synchronous motor capable of delivering 208 kN-m torque would accelerate the rotor in about 5 minutes. A variable frequency drive system ensures a relatively constant torque - speed characteristic during run up. The motor is particularly efficient and retains the high efficiency throughout its speed range. Much of the time however, the motor would only supply torque to overcome friction and windage loss of the HERPC.

When supplying a system with connected generation, the HERPC must follow the local frequency. The rotor speed and its load angle relative to the receiving end system would therefore be constantly trimmed by accelerating / decelerating the rotor using the variable frequency drive train.

Because currently, only low speed HTS motors are available, the drive train must be equipped with a step up gearbox.

An additional advantage of the HTS design is its small size and weight when compared to other conventional motors. The HTS principle could also be applied to the HERPC, with the resulting similar benefits of high efficiency and reduced size and weight.

The copper losses for the 40MVA example machine amount to about 3.4% of rated power, which when taken with other losses result in a slightly less efficient machine than that claimed (96.5%) for the VSC PEC. A better comparison is with a convention synchronous motor of similar power rating. These large machines have been optimized during design and typically operate at efficiencies of 97%. The efficiency of an electromechanical machine however is dependent on the amount and quality of the materials, and improvements may be achieved through design and cost. That is not the case for the PEC for which the main limitations are the semiconductor devices employed.

Unlike the PEC, the HERPC is a fundamental frequency device. Any harmonic distortion produced would be due to manufacturing imprecision or pared designs that allow nonlinear magnetic effects to arise. Fringing flux between the passing rotor and stator pole faces may also be a cause. This is preventable through adequate specification of dimensions and material. Phase unbalance is more likely to occur than harmonic distortion. A small run out of the rotor, or differences in the reluctance of the AC magnetic circuits might be the cause. It is anticipated that the precision obtainable in modern manufacturing is able to reduce these effects to acceptable levels.

#### IV. APPLICATIONS

In offshore oil and gas production facilities, the HERPC may be used to power installations from land based Combined Cycle GT onshore power plants. By interconnecting using HVDC cables, and replacing offshore GTs with electric motors, more reliable and near maintenance free offshore facilities with overall reductions in CO<sub>2</sub> emissions are possible [2].

In the energy utility business the HERPC could replace the PEC inverter. It is likely to offer lower capital expenditure due to space savings and simpler manufacturing methods and materials, and reduce operational costs due to its safer (no exposed high voltages) and very reliable, robust rotating electrical machine construction.

On land based power grid systems, the likely reduction in costs and increased reliability of the HERPC plant over PECs would encourage underground cable installations in place of overhead power lines. Acquisition of the resulting narrower and unintrusive wayleaves by energy utilities would be far easier. The elimination of overhead power lines is commonly seen as a major benefit to the environment.

The HERPC may alternatively be applied as a brushless Synchro, generally used for position sensing applications,

in which case the principal winding would be excited from an AC source.

#### V. CONCLUSION

A HERPC is proposed that converts the format of electric energy directly, without transforming to or from mechanical energy. The HERPC employs an unforced (except for losses) mechanically driven homopolar rotor that carries no windings, to link magnetic flux from field windings, with induction windings, thereby generating output emfs. The HERPC requires neither slip rings nor a brush type commutator. Operating as an inverter, near perfect sinusoidal output waveforms may be obtained. Output frequency is determined by the speed of the driven rotor. The HERPC is suited to the HV power distribution business as the windings may be constructed to withstand hundreds of kV (AC or DC) using modern manufacturing methods. It may also be applied to industrial size three-phase systems fuelled by DC producing renewable energy sources.

By comparison to the PEC the HERPC has expectations of robust construction (as a consequence of rotating machine technology), highly efficient operation, exceptional power quality and dramatic reduction in size and weight. In the offshore power business, where 'Power from Land' is becoming the preferred solution due to safety and environmental reasons, the HERPC may offer an ideal solution for power distribution applications.

#### ACKNOWLEDGMENT

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#### GLOSSARY

AC	Alternating Current
DC	Direct Current
emf	electro motive force
ERPC	Electro-mechanical Rotary Power Converter
GT	Gas Turbine
HERPC	Homopolar Electro-mechanical Rotary Power Converter.
HTS	High Temperature Superconductor
HVDC	High Voltage Direct Current
PEC	Power Electronic Converter
VSC	Voltage Source Converter

## APPENDIX

Stator–rotor overlap area per phase:

$$(1) \quad A_R = \int (M \cdot \pi / 2 \cdot \omega) \cdot \sin(\omega t / M) d(\omega t)$$

$$(2) \quad A_R = (M \cdot \pi) \cdot (1 - \cos(\omega t / M))$$

For a constant reluctance main circuit:

$$(3) \quad \Phi = \frac{i_p \cdot N_p}{3} \cdot \left( \frac{1}{\mathfrak{R}_R} + \frac{1}{\mathfrak{R}_Y} + \frac{1}{\mathfrak{R}_B} \right)$$

$$(4) \quad \frac{d\Phi}{dt} = 0$$

AC winding induced voltage:

$$(5) \quad v_R = \frac{i_p \cdot N_S \cdot N_P}{3} \cdot \frac{d}{dt} \left( \frac{1}{\mathfrak{R}_R} \right)$$

And approximating the reluctance to the airgap:

$$(6) \quad \mathfrak{R}_R = \frac{\ell}{\mu_0 \cdot A_R}$$

$$(7) \quad v_R = \frac{i_p \cdot N_S \cdot N_P \cdot \mu_0}{3 \cdot \ell} \cdot \frac{d}{dt} [M \cdot \pi \cdot (1 - \cos(\omega t / M))]$$

Then:

$$(8) \quad v_{R(rms)} = \pi \cdot \omega \cdot \frac{i_p \cdot N_S \cdot N_P \cdot \mu_0}{3 \cdot \sqrt{2} \cdot \ell}$$

$$(9) \quad P_R = \left( \pi \cdot \omega \cdot \frac{i_p \cdot N_S \cdot N_P \cdot \mu_0}{3 \cdot \sqrt{2} \cdot \ell} \right)^2 \cdot \left( \frac{R}{(R)^2 + (\omega \cdot L)^2} \right)$$

And:

$$(10) \quad P_{output} = 3 \cdot P_R = 3 \cdot P_Y = 3 \cdot P_B$$

$$(11) \quad P_{output} = i_p^2 \cdot R_{eff}$$

Input power:

$$(12) \quad v_p \cdot i_p = i_p^2 \cdot R_p + P_{core} + 3 \cdot i_{R(rms)}^2 \cdot R$$

$$(13) \quad v_p \cdot i_p = i_p^2 \cdot R_p + P_{core} + i_p^2 \cdot R_{eff}$$

Then:

$$(14) \quad R_{eff} = 3 \cdot (\pi \cdot \omega \cdot N_S \cdot N_P \cdot \mu_0 / 3 \cdot \sqrt{2} \cdot \ell)^2 \cdot (R / (R^2 + (\omega \cdot L)^2))$$

$$(15) \quad i_{R(rms)} / i_p = ((\pi \cdot \omega \cdot N_S \cdot N_P \cdot \mu_0) / (3 \cdot \sqrt{2} \cdot \ell)) / \sqrt{(R^2 + (\omega \cdot L)^2)}$$

Symbols:

R,Y,B	red, yellow, blue phases
p	principal winding
s	AC winding
rms	root mean square
R <sub>eff</sub>	effective DC resistance of AC components
P <sub>core</sub>	AC core power loss
ω	angular frequency
A <sub>R</sub>	stator–rotor overlap area per phase
M	stator face amplitude factor
ℓ	length of airgap
μ <sub>0</sub>	4 · π · 10 <sup>-7</sup> (H · m <sup>-1</sup> )
N	number of turns
R	resistance of windings and load
L	inductance of windings and load
P	power dissipated
ℑ	magnetic circuit reluctance
Φ	DC flux
v	phasor voltage or DC voltage
i	phasor current or DC current

The equations predict a typical 40MVA, 0.9 power factor device with the following parameters:

v <sub>R(rms)</sub>	: 6.35kV, (11kV line)
v <sub>p</sub>	: 100kV (±50kV)
ω	: 2 · π · 50
rotor speed	: 3000 rpm
N <sub>S</sub>	: 50
N <sub>P</sub>	: 12
A <sub>R</sub>	: 1.3 m <sup>2</sup>
Airgap	: 0.01 m
R <sub>eff</sub>	: 278Ω

The analysis assumes negligible leakage reactance and conduction losses compared to the load. The reluctance of the magnetic circuit is dominated by the airgap. The breadth and width of the stator–rotor overlap area per phase is 1.43m.

For the arrangement used, namely Figure 1 but with one pole face per phase, the maximum flux density occurs in the stator limb that resides inside the rotor. The area at the entry point is critical. It is chosen as 75% of the total rotor cross sectional area. The maximum flux density is 1.6T.

The rotor circumference is dimensioned to span one stator pole face and one inter pole face. The rotor diameter is therefore 0.91m.

With a full load current of 3636A, and a current density of 2A per mm<sup>2</sup>, each AC copper coil is fabricated with an inner radius of 715mm, outer radius of 1045mm and a coil depth of 330mm. A 10% allowance is made for insulation.

The rotor length is determined by the three side-by-side coils each offset at 120 degrees. The rotor length is 4.7m. For materials that have a density similar to steel, the rotor dimensions result in an inertia of 1110 kg · m<sup>2</sup>.

The principal winding is wound with 50kV, 150mm<sup>2</sup> Cu, XLPE HVDC cable of minimum bending radius 500mm, outside diameter 50mm and weight 7kg · m<sup>-1</sup>.