

Improved Jiles-Atherton Hysteresis Model for Converter Transformer Controlled Switching Assessment in Nelson River Bipole III HVDC System

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SUMMARY

Controlled switching (CS) technology considering remanence flux had been successfully verified in conventional AC applications on transformers of single-phase units with a delta-connected winding and / or with a three-limb core via a process termed flux equalization [1-4]. The adaptation of CS in Nelson River Bipole III HVDC system reflected the latest technology and a world-first HVDC application. There were uncertainties on accuracy of CS flux estimation under various HVDC operating conditions during normal or protection initiated emergency shut-down of valve group (VG) and converter transformers, as well as the effectiveness of CS control strategy for a pair of converter transformers with a three-phase five-limb core switched by a common circuit breaker.

In fulfillment of design requirements, Riel converter transformers were constructed with high-induction and low-loss M3 grade ferromagnetic grain oriented electrical steel (GOES) and were equipped with on-load tap changers (OLTC) of a wide voltage regulation range up-to 56%. The selected CS device always assumes a fix tap position at nominal voltage level and does not consider any OLTC movements. Such scheme would function well when OLTC remains unchanged during de-energization and subsequent energization events. However, large tap position movements of Riel converter transformer OLTC following protection initiated HVDC emergency shut-down can induce significant flux calculation error on a CS device. Feeding OLTC information to CS controller risked a hefty capital cost and unverified modifications of CS algorithm in an already aggressive scheduling.

A hysteresis model with an overall accurate description of magnetization at various excitation levels was deemed crucial to verify CS adaptation for Riel HVDC converter transformers. Classic Jiles-Atherton (J-A) hysteresis model is popular in engineering applications but identification of its model parameters remains a difficult undertaking. Published identification techniques of J-A hysteresis model parameters mostly considered only a single hysteresis loop and repeatedly omitted magnetization curve characteristics. This paper presents a novel and holistic multi-objective constrained Particle Swarm Optimization (PSO) process for the identification of J-A model parameters using a set of published hysteresis loops together with magnetization curve measurements of a M3 grade GOES simultaneously. An improved J-A hysteresis model is introduced to substantially enhance the prediction of minor and major hysteresis loops and magnetization curve concurrently.

KEYWORDS

Line Commutated Converter (LCC), Nelson River HVDC System, Converter Transformer, Controlled Switching (CS), Ferromagnetic Remanence, Jiles-Atherton (J-C), Grain Orientated Electric Steel (GOES), Particle Swarm Optimization (PSO)

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1. INTRODUCTION

The new Bipole III Line Commutated Converter (LCC) HVDC transmission system inaugurated in 2019 represents a significant long-term investment in reliability and security of the bulk energy infrastructure of Manitoba Hydro, Manitoba, Canada. Manitoba Hydro mainly depends on HVDC transmission to transfer northern hydro electrical generation to southern load centres and exports in the province. Bipole III HVDC system provides an alternative transmission outlet and additional 2000 MW north-to-south transfer capacity in a west corridor strategically separated from the common Interlake Transmission Corridor of the existing Bipole I & II LCC HVDC facilities. It originates from Keewatinohk rectifier station in the north and terminates at Riel inverter station in the south. The vintage Bipole I & II originate from northern Radisson and Henday rectifier stations respectively and terminate at a common southern site of Dorsey inverter station, about 40 km from Riel station.

Transformers in LCC HVDC converter stations are typically rated at several hundreds of megawatts and constructed with high quality core material. Direct energization of such transformers can cause sustained inrush currents and adversely impact LCC converter operations and other station equipment. A circuit breaker equipped with judiciously selected pre-insertion resistor (PIR) has been traditionally practiced for converter transformer energization in most HVDC systems, including Manitoba Hydro's Bipole II [5]. A hybrid solution of PIR and synchronized point-on-wave switching neglecting remanence flux has been installed during Transpower Pole 3 HVDC modernization project in New Zealand [6]. The state-of-the-art controlled switching (CS) device accounting for remanence flux has been successfully deployed by Manitoba Hydro for a conventional AC power transformer of single-phase unit with a delta winding [2]. This scheme always estimates transformer core remanence flux during de-energization events and identifies optimal energizing instant of the phase with highest remanence flux first followed by a simultaneous energization of two remaining phases a few cycles later. The same scheme was employed for paired converter transformers of three-phase five-limb construction in Bipole III HVDC system at Riel station.

Controlled switching strategy considering remanence flux has been widely published and verified for AC power transformers of single-phase units with a delta-connected winding and / or with a three-limb core via a process termed flux equalization [1-4]. No precedent installation of this CS scheme has been previously reported in classic LCC HVDC applications or configuration of two three-phase five-limb transformers switched by a common circuit breaker. For a holistic performance evaluation of CS adaptation in Riel Bipole III HVDC system, accurate and proper description of converter transformer magnetic flux behavior under various excitation conditions and magnetization curves were pivotal.

Hysteresis is an intrinsic physical attribute of ferromagnetic materials like the Grain Oriented Electric Steel (GOES) used in Riel converter transformer core construction and the underpinning cause of transformer inrush transients. Numerous ferromagnetic hysteresis models have been proposed and only a few models like classic Jiles-Atherton (J-A) model truly respect the underlying material physics and mechanisms of microstructures and macroscopic properties. Despite its popularity in engineering applications, identification of J-A model parameters remains a major undertaking. An increasing number of artificial intelligence methods such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Direct Search Method (DSM) have been explored and endorsed for this endeavour in literatures. These approaches generally transform model parameters into search space dimensions and evaluate agreement between calculated and measured quantities by correctly conceived fitness / objective functions. Extensive literature review concludes that most if not all identification of J-A model parameters was based on a single hysteresis loop for a rather limited excitation range and repeatedly excluded magnetization curve characteristics.

2. CONTROLLED SWITCHING FOR RIEL BIPOLE III HVDC APPLICATION

Given the close electrical vicinities, Nelson River HVDC systems feature a tightly-coupled three-bipole, multi-infeed and multi-egress topology and demonstrate characteristics and behaviours of

relatively high multi-infeed interaction factors (MIIF) [7]. In this operating environment, unmitigated electromagnetic transients like converter transformer energization inrush currents at Riel station can propagate to nearby Dorsey inverter station and provoke valve group (VG) commutation failures hence adversely affecting Bipole I & II HVDC operations [8-9]. As remedies, circuit breakers complemented by the latest controlled switching technology with remanence flux estimation were considered for energizing Bipole III HVDC converter transformers at Riel station based on technical and economic merits – a world-first application of its kind. Guided by remanence flux estimation, each CS device determines strategic closing instants of a common circuit breaker energizing a pair of converter transformers (YNy0 and YNd1) of three-phase and five-limb core construction as illustrated in Figure 1.

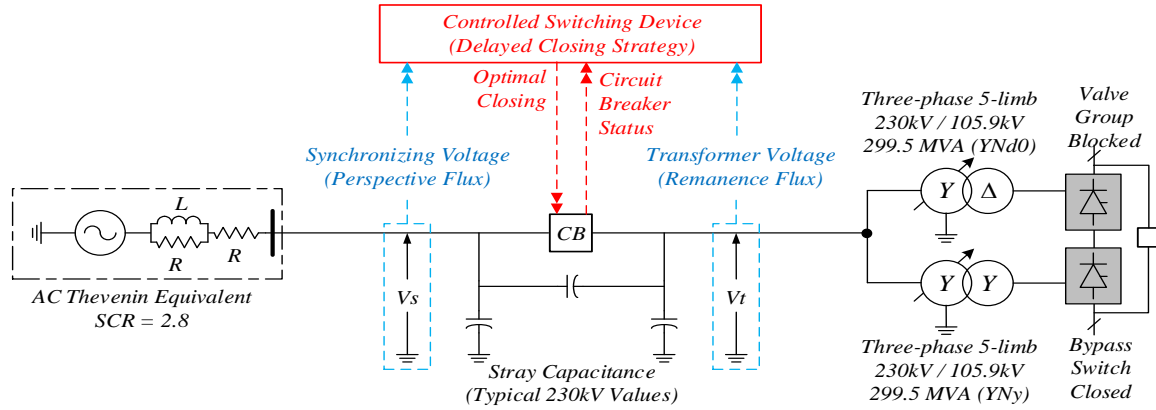
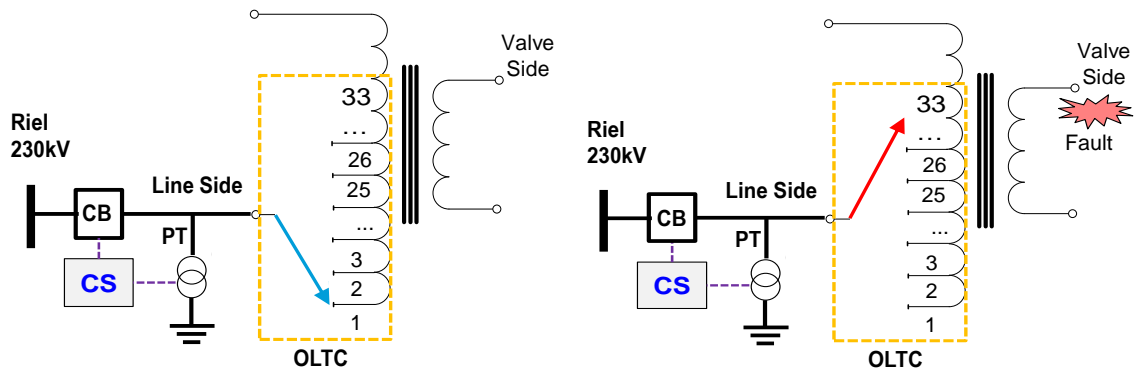


Figure 1 Illustration of controlled switching for paired Riel HVDC converter transformers

For optimal and economic operations, Bipole III converter transformers are equipped with on-load tap changers (OLTC) with an extended range of 33 tap positions and 56% voltage regulation. By vendor's design, OLTC is always positioned at tap 1 for converter transformer energization as a mean to curb inrush currents with a relatively higher leakage inductance and lower excitation / perspective flux. During a normal shutdown of converter transformers and valve groups, OLTC is deliberately positioned at tap 1 with the highest number of winding turns as shown in Figure 2 (a). In the case of a protection initiated shutdown, protective action prevails and opens circuit breakers quickly so OLTC remains at pre-contingency tap position as seen in Figure 2 (b). This OLTC movement unaccounted by Riel CS controller creates a large error, up to 56% in the worst scenario, on the remanence flux estimation. Feeding OLTC position information risks a substantial capital cost and unverified modification on CS control algorithm. Accurate representation of Riel converter transformer flux and remanence flux behaviours under this large excitation range was essential and an integral part of the advanced transformer simulation model to verify this CS scheme [10].



a) Normal VG and converter transformer shutdown

b) Protection initiated VG and converter transformer shutdown

Figure 2 Riel converter transformer OLTC movements in normal and protection initiated shutdowns

3. J-A MODEL PARAMETERS' IDENTIFICATION BY MULTI-OBJECTIVE PSO

3.1 Published Data Selection, Preparation and Refinement

Technical specifications of Riel converter transformer stipulate strict requirements on permissible core and power losses, dimension consideration for transportation and more. In fulfilment of these conflicting design criteria, Riel converter transformer core was constructed from Nippon 23 mm M3 grade domain-refined (DR) high magnetic induction Grain Oriented Electrical Steel (GOES). Given the data unavailability of Nippon GOES, catalogue measurements of a compatible 23 mm M3 grade domain-refined high-induction GOES specimen published by AK Steel have been considered instead [11]. Published measurement data was extracted, interpolated, resampled at a higher resolution, and reconstructed into monotonic data series in MATLAB as shown in Figure 3.

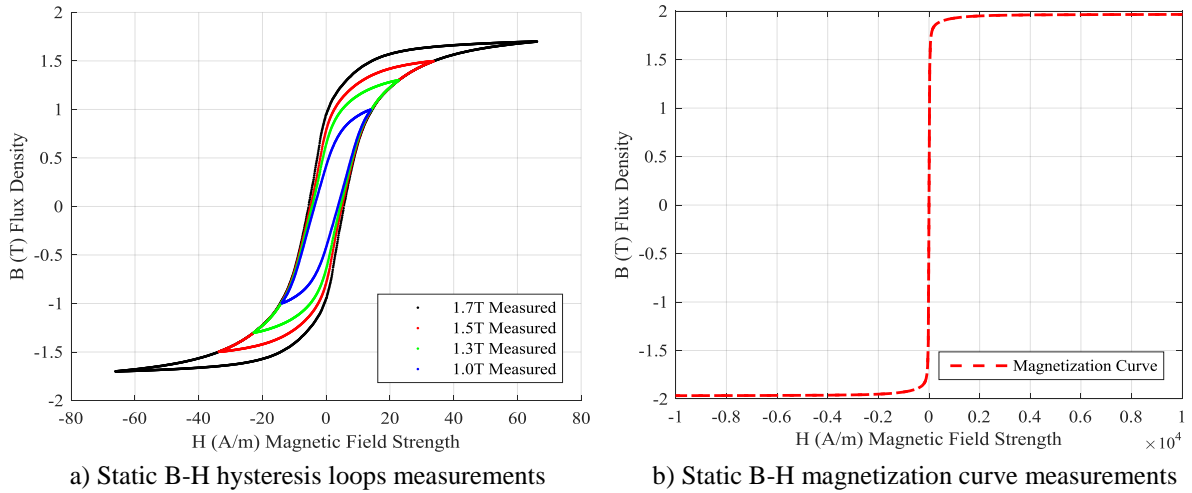


Figure 3 Extracted measurements of AK Steel 23 mm M3 Grade DR GOES

3.2 J-A Theory, Model Parameters and Key Formulations

The J-A theory has conceptualized on physical phenomenal and fundamental hypothesis of reversible, irreversible and anhysteretic magnetization components denoted as M_{rev} , M_{irr} and M_{an} respectively and developed a system of inexplicit ordinary differential equations (ODEs) that characterize hysteresis loops for ferromagnetic materials [12-13]. Extending original J-A model, one of the key differential relationships of total magnetization M and induction B as expressed in (1) offers many advantages over the differential susceptibility dM/dH formulation for incorporation into an advanced duality theory based three-phase five-limb transformer model in electromagnetic transient program (EMTP) like PSCAD/EMTDC [10].

$$\frac{dM}{dB} = \frac{\frac{(M_{an} - M)}{k\delta} + \frac{c}{\mu_0} \frac{dM_{an}}{dH_e}}{1 + \mu_0(1 - \alpha) \left(\frac{(M_{an} - M)}{k\delta} + \frac{c}{\mu_0} \frac{dM_{an}}{dH_e} \right)} \quad (1)$$

where anhysteretic magnetization M_{an} is described by an alternative expression as in (2) for higher degrees of freedom compared to the modified Langevin function in classic J-A model; α is the inter-domain coupling factor, c ($0 < c < 1$) is the domain flexing parameter, k is the domain pinning parameter, H_e is the effective magnetic field strength, a_1, a_2 & a_3 ($a_2 > a_1 > 0$, $a_3 > 0$) are the form factors of anhysteretic magnetization function, μ_0 and δ are the vacuum permeability and conditional constants respectively [10], [14].

$$M_{an} = M_s \cdot \frac{a_1 \cdot H_e + H_e^2}{a_3 + a_2 \cdot H_e + H_e^2} \quad (2)$$

where M_s is the saturation magnetization - an intrinsic property of a given magnetic material.

A total of seven parameters need to be identified using a set of four hysteresis loops and magnetization characteristics of the AK 23mm M3 grade DR GOES.

3.3 Identification of J-A Model Parameters using Multi-objective Constrained PSO

Particle swarm optimization (PSO) is a biologic population derived computation intelligence technique conceptualized on the stochastic and dynamic social behaviour of each particle, interaction among particles and collective movement of the entire swarm population [15-16]. Each particle represents a potential solution of J-A hysteresis model and encompasses a total of seven model parameters that are randomly initialized with attributes such as spatial position, velocity, and inertia in respective search space and given the ability to record its personal best history. Ill-defined J-A parameters are prone to yield a poor or non-physical solution, so a constrained initialization process has been developed to eliminate and replace bad outlier particles and to encourage an accelerated convergence [10]. In any given iteration, particles move in their search space domains, evaluate their fitness against target objectives, record personal best history and promote the best personal performance as the new global best solution of the entire swarm. Iteratively, each particle adjusts its movement by learning from the new global best and personal history and rapidly converges to an optimal solution or terminates the process when the maximum number of iterations is exceeded.

Fitness functions are conceived to evaluate the quality and performance of each particle's positions in multi-dimensional spaces for an optimal set of J-A model parameters. They minimize the overall disparity between calculated and measured quantities based on fitness criteria. Accurate hysteresis description is imperative in remanence flux prediction during a power transformer de-energization; whereas correct representation of magnetization curve is equally vital in determining inrush transients in the subsequent energization. Magnetization induction B and field intensity H calculated by J-A model was compared with published measurement of a cluster of hysteresis loops and magnetization curve. Enclosed areas by hysteresis loops per cycle that signifies static loss were also included as shown in Figure 3 to further expedite the convergence [17]. All quantities are normalized by measured maximums respectively to equalize individual aspect contribution as data points on different hysteresis loops and magnetization curve bear uneven weight contribution toward the fitness evaluation.

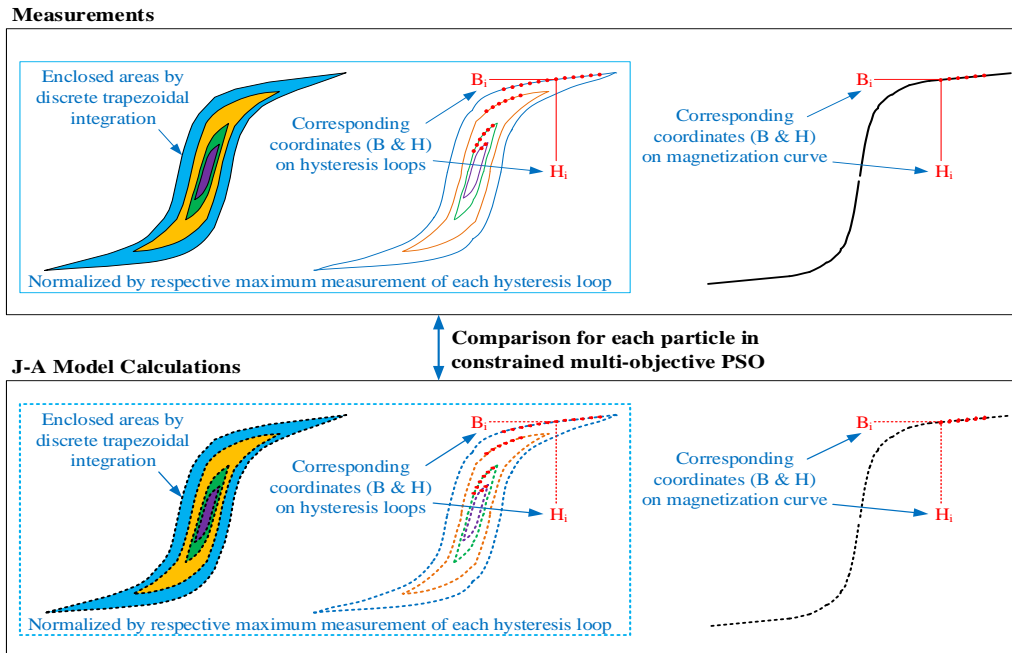


Figure 3 Qualitative Illustration of PSO Multi-objective Fitness Functions

With the proposed multi-objective constrained PSO process, identification of J-A hysteresis model parameters yields satisfactory agreements between calculated and measurement quantities for each individual hysteresis loop and magnetization curve but fails to produce one single set of model

parameters capable of closely describing all four hysteresis loops and magnetization curve simultaneously as seen in Figure 4, where pronounced deviations, especially near B axis intercept points, are present [10]. These discrepancies in turn translate to erroneous remanence flux prediction [10]. It is recognized that J-A model parameters optimized for a single hysteresis loop are only valid for a rather limited range of the applied field which is perceived a basic limitation of the classic J-A model with constant parameters [18]

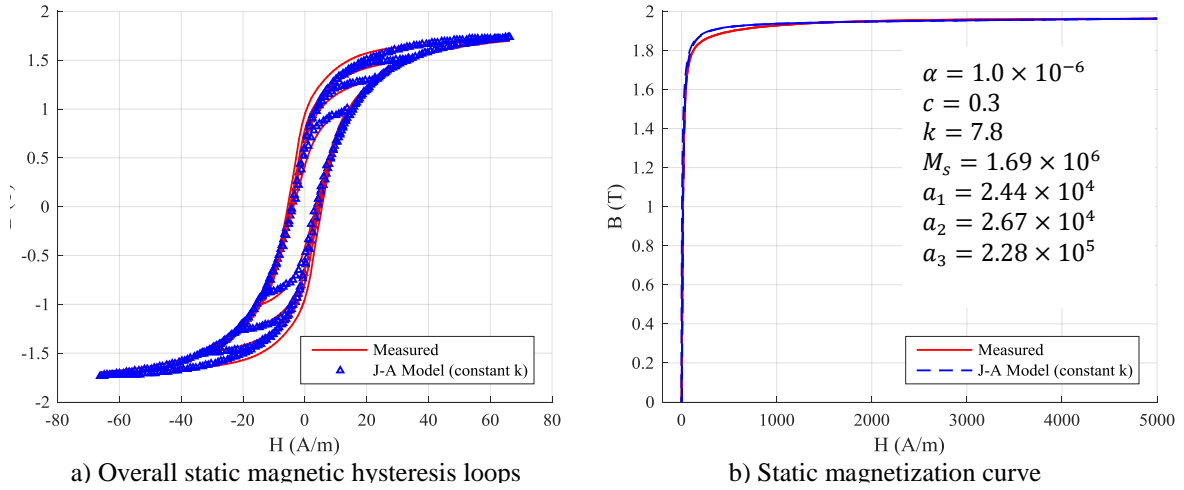


Figure 4 Measured & calculated B-H loops and magnetization curve (J-A model & constant parameters)

4. MODIFICATION AND IMPROVEMENT OF J-A MODEL

Hysteresis loop width is primarily dictated by the pinning parameter k [19]. It is therefore necessary to adjust k and such notion is in accordance with J-A theory and parallel to many publications [13]. Several modifications of J-A model with a variable k have been proposed based largely on empirical approaches [14]. In this report, a novel systematic process is proposed to define the pinning parameter as a function of magnetization level utilizing the multi-objective constrained PSO process therein.

The proposed variable pinning parameter k is derived as a function of magnetization M which is more directly related to the internal dynamic and behaviour of magnetic structures and bounded by lower and upper limit values of zero and M_s . Upon optimization of all four hysteresis loops separately, a functional relationship of variable k with relative magnetization level M/M_s is obtained in (3) and plotted in Figure 5. Based on the observed relationship, a power series function is hypothesized to alter the hysteresis loop width specifically targeting the areas of disparities as seen in Figure 4.

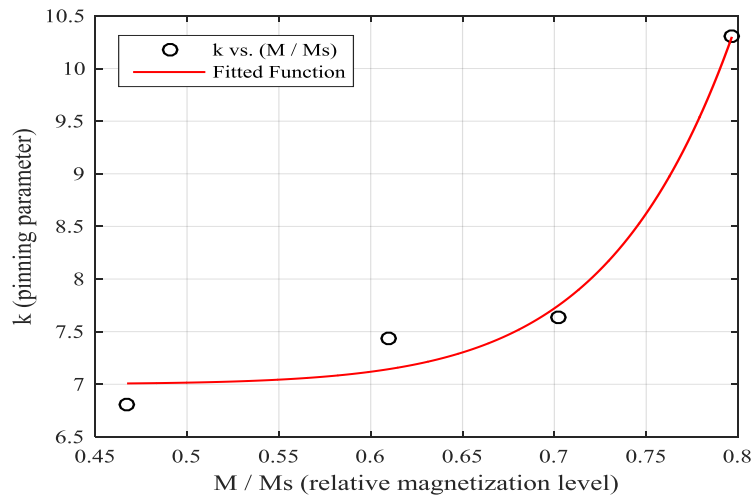


Figure 5 Variable of pinning parameter k with relative magnetization level M/M_s

$$k_{eff} = k_s \left(1 + pk_1 \cdot \left(\frac{M}{M_s} \right)^{pk_2} \right) \quad (3)$$

where k_{eff} is the effective domain pinning parameter, k_s is a static pinning parameter at zero magnetization, pk_1 and pk_2 are two new coefficients to amend k_s only at targeted arears in Figure 4.

Identification of these nine parameters ($\alpha, c, M_s, a_1, a_2, a_3, k_s, pk_1$ & pk_2) for the modified J-A model was then repeated using the previous multi-objective constrained PSO for a group of four hysteresis loops and magnetization curve simultaneously. It is demonstrated in Figure 6 that the modified J-A model with the proposed variable pinning parameter k significantly improves the agreement of measured and calculated hysteresis loops and magnetization concurrently, thus validating the proposed modification.

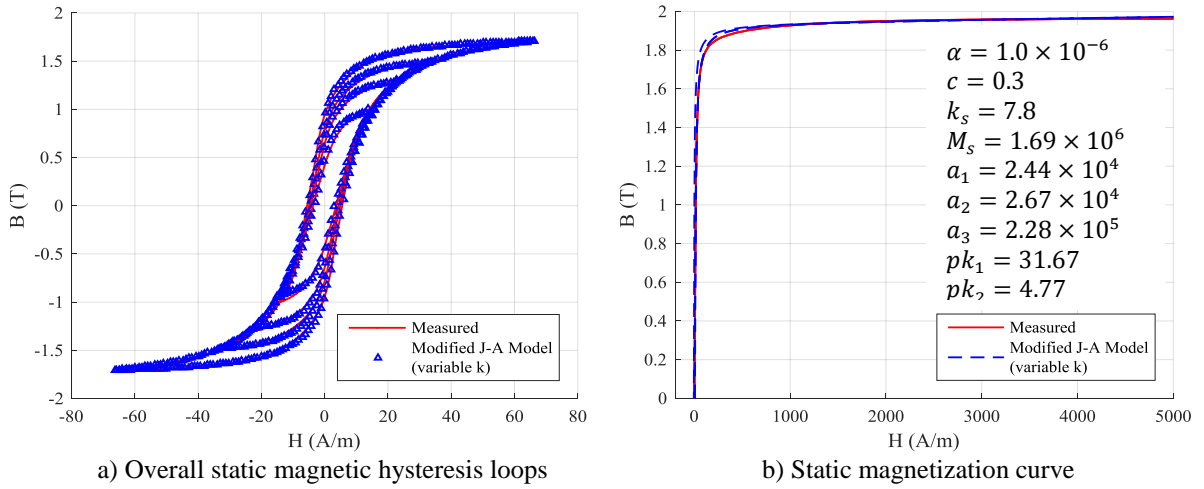


Figure 6 Measured & calculated B-H loops and magnetization curve (modified J-A model & variable k)

5. CONCLUSIONS

Proper and accurate representation of hysteresis and magnetization curve of HVDC converter transformers was crucial for a holistic evaluation of the adaptation of controlled switching technology with remanence flux estimation in Riel Bipole III HVDC project. Despite its popularity in engineering application, identification of classic J-A hysteresis model parameters remains a major undertaking. A novel multi-objective constrained PSO technique has been developed and seen to effectively identify optimal model parameters of classic J-A model using individual hysteresis loop and magnetization curve simultaneously. In reorganization of the limitation of classic J-A model, a new variable pinning parameter k has been proposed and demonstrated to significantly improve the overall accuracy of description of ferromagnetic behaviours of a group of four hysteresis loops and magnetization curve simultaneously. This improved model can then be incorporated into advanced duality-based transformer models in PSCAD/EMTDC for a holistic performance assessment of the adaptation of CS in Riel Bipole III HVDC application [10].

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