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Development of Clarke and Park Transforms Visualization Software Using Python

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ABSTRACT

Three-phase electrical systems are commonly utilized in many industrial applications. In particular, they are used in transmission and distribution lines, as well as in the operation of asynchronous motors. Despite their widespread use, three-phase electrical systems are challenging to model and analyze because of the time-depending parameters. In order to overcome these challenges, some mathematical methods such as Clarke and Park transforms are performed. In this study, to ease the understanding of Clarke and Park transforms, a software application is developed. The application demonstrates the effects of changing the voltage, frequency, and phase parameters on the Clarke and Park transforms. In the proposed application, users can convert 3-phase (ABC) axes to 2-phase (αβ) axes, 2-phase (αβ) axes to reference (dq) axes. Application can also convert 2-phase axes to 3-phase axes with the inverse Clarke and Park transforms. During the transformation, it visualizes three separate sequences with a single parameter input, eliminating the need for repeated parameter input for each axis. Mathematical modelling and user interface development of the application are performed in Python programming language.

Python Kullanılarak Clarke ve Park Dönüşümlerini Görselleştirme Yazılımının Geliştirilmesi

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Yazılım

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ÖZ

Üç fazlı elektrik sistemleri birçok endüstriyel uygulamada yaygın olarak kullanılmaktadır. Özellikle iletim ve dağıtım hatlarında ve asenkron motorların çalışmasında kullanılırlar. Yaygın kullanımlarına rağmen üç fazlı elektrik sistemlerinin zamana bağlı parametrelerden dolayı modellenmesi ve analizi zordur. Bu zorlukların üstesinden gelmek için Clarke ve Park dönüşümleri gibi bazı matematiksel yöntemler kullanılır. Bu çalışmada, Clarke ve Park dönüşümlerinin anlaşılmasını kolaylaştırmak için yazılım programı geliştirilmiştir. Uygulama, voltaj, frekans ve faz parametrelerinin değiştirilmesinin Clarke ve Park dönüşümleri üzerindeki etkilerini göstermektedir. Geliştirilen programda, kullanıcılar 3 fazlı (ABC) eksenden 2 fazlı (αβ) eksene, 2 fazlı (αβ) eksenden referans (dq) eksenine dönüşüm yapabilmektedirler. Dönüşüm sırasında, tek bir parametre girişi ile, üç ayrı dizi görselleştirilerek, her eksen için tekrarlanan parametre girişi ihtiyacı ortadan kaldırılmıştır. Uygulamanın matematiksel modellemesi ve kullanıcı arayüzü Python programlama dili kullanılarak geliştirilmiştir.

1. INTRODUCTION

Electrical systems have been used in all areas, and they need to be controlled. There are many control systems and different algorithms. Every one of them is invented for different need of use. Some electrical systems need precise control, some of them need fast response, some of them need basic systems or algorithms [1,2]. Every need caused the invention of different control systems. Clarke and Park transforms are invented for modelling of electrical systems and used in these control systems. They were invented to ease the control of three phase systems. They are used in the control of both power grids and three phase motors [3-5].

Clarke and Park transforms used in different areas. When extracting phase information from a three-phase disturbed signal, a phase detector which is based on Clarke transform and arctangent function is widely used [6]. When detecting and classifying the transmission line faults, a fault identification matrix (FIM) based on the change in the resultant current samples of α-β components is used [7]. For time-domain modeling framework for three-phase unbalanced AC power systems, g-dq0 transform is derived as a generalized variant of dq0 transformation [8]. As g-dq0 transform, Reduced Reference Frame (RRF) which improves the performance of the classical Fortescue, Clarke and Park transformations is proposed for unbalanced three phase four wire systems. The RRF transformation represents any unbalanced three phase sinusoidal magnitude with just two components even if the zero-sequence component is present [5]. For detecting the fault current from the switching currents, and other transient and loading conditions to improve the longitudinal differential relay performance, Clarke transform is used [9].

Clarke and Park transforms simplify the analysis and control of the 3-phase systems by converting them into 2-phase reference frames. This conversion facilities the design of control algorithms such as field-oriented control (FOC), direct torque control (DTC) and field weakening control (FWC), enhances the understanding of system behavior under different operating conditions, and makes the modelling and analysis easier [10,11].

Field oriented control is one of the most used motor control algorithms. In FOC not only magnitude and frequency are adjusted, but also the instantaneous values of voltage, current, and flux space vectors, which allows transient operation. FOC uses Clark-Park transforms to control motor. For example, 3-phase amplitudes and phase values can be controlled via d and q sequences, so 4 parameters can be controlled by 2 parameters [12,13]. This conversion proceeds like this: When V_d is 100V and V_q is 0V, 3-phase amplitudes become 100V and phase becomes 0˚, when V_d is -100V and V_q is 0V, 3-phase amplitudes become 100V and phase becomes 180˚, when V_d is 0V and V_q is 100V, 3-phase amplitudes become 100V and phase becomes 270˚, when V_d is 0V and V_q is -100V, 3-phase amplitudes become 100V and phase becomes 90˚. Phase angle not only becomes the multiples of 90. It can be modified by changing the V_d and V_q parameters as the users wish. For example, if V_d is 90V and V_q is 45V, 3-phase amplitudes become approximately 100V and phase angle becomes approximately 26.6˚ [4,14].

Although practical applications and visualizations of Clarke and Park transforms are important, it is also hard to understand for the students and practitioners who are new to the field. Conventional teaching methods generally use static diagrams and equations, that maybe not fully convey the dynamic relationship between reference frames to students. Therefore, there is a need for an application to fill the gap between theoretical concepts and real-world implementations.

In return to this need, this article provides the development of user-friendly software application to calculate and visualize the Clarke and Park transforms. The application comes with a graphical user interface (GUI) that allows users to enter the system parameters, perform the transformations, and observe the resulting waveforms and vector diagrams in real time. The application does all the calculations that are needed to visualize waveforms of all three sequences, so users can see waveforms and reference frame vectors of all three sequences by only entering one of the sequence values. With the real time process, users can see how the difference in parameters can affect the three sequences in time and vector domain. By enabling practical experimentation, the tool serves as both an educational resource and practical aid for students and engineers who are working with 3-phase systems.

2. MATERIALS AND METHODS

2.1. Motor Control

Motor control methods can be categorized as two groups: vector and scalar control [12,13]. Scalar control consists of SWC (square-wave control), voltage control, frequency control and V/f control (Volts per Hertz) method [13,15]. SWC mainly used to drive BLDC (brushless DC) motors. In this algorithm, the angle between the stator magnetic field and rotor magnetic field fluctuates from 60° to 120°. The rotor of the motor needs to commutate six times per turn. Every commutation cause torque ripple. These ripples do not only affect speed accuracy, and they also cause vibration that affects the system stability. Instead of SWC, using FOC algorithm provides better speed response and torque stability. In a study while driving BLDC motors, the average overshoot, average rise time, and average settling time of FOC algorithm (10.43%, 0.44 s, 0.43 s) is less than SWC algorithm (15.68%, 0.67 s, 0.95 s) [1].

In V/f control algorithm, voltage, current, frequency, pole and flux are the main parameters. By changing the amplitude of these parameters, V/f control can be achieved. While the frequency is constant, by changing the pole, the speed of the motor can be controlled, but after manufacturing, the pole cannot be changed. Similarly, by changing the frequency, synchronous speed can be controlled. If the frequency increases, speed will increase but starting and maximum torques reduce. To maintain the flux constant, the ratio of voltage and frequency must be constant. If the flux is constant, maximum torque is constant, but starting torque will reduce [12,13].

Vector control consists of FWC (field weakening control), DTC (direct torque control), sliding mode control, adaptive control, fuzzy control, MPC (model predictive control) and FOC (field-oriented control) [2,16]. Induction motor field weakening control uses traditional $1/\omega_r$ method. Reference motor flux and above base speed is inversely proportional to the actual speed of the rotor. In this method, excitation current is given without considering voltage influence current regulation, so to achieve the optimal field weakening area is difficult. In this control strategy, it is required to set up a complex model and it is strongly dependent on the motor parameters, so it has poor robustness. FWC limits the voltage, reduces the magnetic field intensity, arranges enough torque current to improve speed and torque output capacity. Maximum torque mainly depends on the current limitation and magnetic flux level, so the reasonable distribution of current is the key to achieving torque increase [11].

The objective of DTC is to maintain torque and stator flux vector within two hysteresis bands. When the stator flux vector modulus is kept constant, the value of the rotor flux decreases as the load on the motor increases. The motor can produce any torque the dc- link voltage allows it. Unlike FOC, DTC does not require coordinate transformation, current control loop and separate pulse width modulator. The structure of DTC is simple, and it directly obtains PWM from hysteresis comparator to control the motor. Because it uses hysteresis, DTC has high torque, current, flux ripples, vibration and noise [2,16,17].

MPC is used control various motors [2,18]. If it is used to control permanent magnet synchronous motors (PMSM) is mainly divided into two: MPCC (model predictive current control) and MPTC (model predictive torque control). For MPCC, generally the predictive model is derived based on control increment and construct the cost function in the form of control increment, while in some applications, control quantity is directly used for the design. Control Increment-Based MPC controller can only limit the output control quantity indirectly, whilst Romberg type Control Quantity-Based MPC controller can directly limit the output control quantity. In MPCC, the increment of control quantity is controlled to eliminate unknown disturbance [2].

Field oriented control first proposed in 1972, with the objective of competing against the separately excited DC machines which have independent control of current and flux. FOC motor driver control unit is mainly composed of main controller circuit, a three-phase full-bridge inverter circuit, a three-phase current sampling circuit, an overcurrent protection circuit, a bus voltage sampling circuit, a Hall sensor signal sampling circuit, and a power supply circuit. FOC can be implemented in a direct way and indirect way. For a direct version, the angle of flux space vector is sensed directly and in an indirect version estimated slip and rotor speed are used to calculate the angle of the flux. To obtain the maximum torque, stator flux must be orthogonal or at 90° to rotor flux. Alternative names of these fluxes are currents of the quadrative axis and direct axis. Quadrative axis is aligned with torque compenent and direct axis is aligned with flux compenent. If the angle between them is 0°, motor does not spin. As the angle starts to increase so the so does the torque. FOC seeks to maintain the angle between them at 90°. To obtain the stator flux (quadrative axis current – torque compenent) and rotor flux (direct axis current – flux compenent) clarke and park transforms are used [10,19,20].

2.2. Clarke-Park Transforms

Before implementation of any electrical system, it will be modelled, studied, analyzed and tested in simulation programs. For these actions and control of the electrical systems, accurate modelling is an important factor [21]. For modelling and control, many transform formulas have proposed such as Clarke, Park, Concordia, Kimbark and Boyajyan, Koga, Rama Rao, Fourier, Wavelet and S. Each of these coordinate's systems are defined by its own transformation matrix [22-25]. For this article, Clarke and Park transforms are chosen for their simplicity and global usage.

Both Clarke and Park transforms are invented with the intention of to ease the control of three-phase systems. During 1920, Park generalized Blondel's Two-Reaction Theory of Synchronous Machines. This method solves the armature fluxes in a salient machine along the two axes: quadrative and direct axes. In the 1930s, Clarke made a series of modifications to symmetrical components. These modifications ease the calculation of the unbalanced three-phase systems as they do not require the α operator (1/120◦) or complex numbers [4]. "$dq0$" based transforms used on wide variety of applications for solving objectives of Electrical Engineering and Power Electronics such as control of electric machines and drives, multimachine modelling, multi-inverter modelling, microgrid simulation, phase-locked loops (PLL), active power filters, VSI as a supply for standalone loads with the renewable energy sources, doubly fed induction motor dynamic model, fault-detection operation mode for an induction motor, three-phase power circuit analysis, three-phase voltages estimation, coordinates transformation of three-phase quantities, AC-DC converter theory and power quality [4,14,22,25].

Clarke transform converts 3-phase rotational frame (A, B, C) to a 2-phase reference frame (α, β). A 3-phase symmetrical system can be defined in Equation (1-3).

$$V_A = V_m sin(\omega t) \tag{1}$$

$$V_B = V_m sin\left(\omega t + \frac{2\pi}{3}\right) \tag{2}$$

$$V_C = V_m sin\left(\omega t - \frac{2\pi}{3}\right) \tag{3}$$

The conversion is given in Eq. (4-6).

$$V_\alpha = \frac{2}{3}\left(V_A - \frac{1}{2}V_B - \frac{1}{2}V_C\right) \tag{4}$$

$$V_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}V_B - \frac{\sqrt{3}}{2}V_C\right) \tag{5}$$

$$V_0 = \frac{2}{3}\left(\frac{1}{2}V_A + \frac{1}{2}V_B + \frac{1}{2}V_C\right) \tag{6}$$

V_α and V_β represents α and β sequences. Zero sequence is represented by V_0 and for the balanced systems value of it is zero. Inverse Clarke transform serves as to convert a 2-phase system to a 3-phase system, and for a balanced system, the conversion can be seen in Equation (7-9).

$$V_A = V_\alpha \tag{7}$$

$$V_B = \left(-\frac{1}{2}V_\alpha + \frac{\sqrt{3}}{2}V_\beta\right) \tag{8}$$

$$V_C = \left(-\frac{1}{2}V_\alpha - \frac{\sqrt{3}}{2}V_\beta\right) \tag{9}$$

It can be observed that there is a 90° phase difference between V_α and V_β. It means that sinusoidal signals of α and β sequences have also 90° phase difference between each other.

Park transform is also known as direct-quadrature transform. It is used to transform a 2-phase fixed reference frame (α, β) to 2-phase rotary reference frame (*d, q*) and the transform is in the Equation (10,11).

$$V_d = \cos(\theta)\, V_\alpha + \sin(\theta)\, V_\beta \tag{10}$$

$$V_q = -\sin(\theta)\, V_\alpha + \cos(\theta)\, V_\beta \tag{11}$$

θ (reference angle) is obtained in terms of V_α and V_β by the Eq. 12.

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \tag{12}$$

V_d and V_q represents the direct and quadrature axes. θ, the ratio between V_α and V_β, is used for calculation of 2-phase rotary frame axes. Inverse Park transform converts 2-phase time dependent reference frame to a 2-phase fixed reference frame. Transform equations are given in Equation (13,14), the frequency of the system used for finding the reference angle and the equation to find it is given in Equation 15.

$$V_a = \cos(\theta)\, V_d - \sin(\theta)\, V_q \tag{13}$$

$$V_b = \sin(\theta)\, V_d + \cos(\theta)\, V_q \tag{14}$$

$$\theta = \frac{\pi}{2} - 2\pi f t \tag{15}$$

Clarke-Park transform is the name of the combination of these two transforms. It combines the formulas of these two and the equations of it are given in Equation (16-18).

$$V_d = \frac{2}{3}\left(\cos(\theta)\, V_A + \cos\left(\theta - \frac{2\pi}{3}\right) V_B + \cos\left(\theta + \frac{2\pi}{3}\right) V_C\right) \tag{16}$$

$$V_q = \frac{2}{3}\left(\sin(\theta)\, V_A + \sin\left(\theta - \frac{2\pi}{3}\right) V_B + \sin\left(\theta + \frac{2\pi}{3}\right) V_C\right) \tag{17}$$

$$\theta = \tan^{-1}\left(\frac{V_A - \frac{1}{2}V_B - \frac{1}{2}V_C}{\frac{\sqrt{3}}{2}V_B - \frac{\sqrt{3}}{2}V_C}\right) \tag{18}$$

Inverse Clarke-Park transform converts 2-phase rotary frame to 3-phase rotational frame and is the combination of inverse Clarke and inverse Park transform. The conversion equations are given in Equation (19-22).

$$V_A = \cos(\theta)\, V_d - \sin(\theta)\, V_q \tag{19}$$

$$V_B = \cos\left(\theta - \frac{2\pi}{3}\right) V_d + \sin\left(\theta - \frac{2\pi}{3}\right) V_q \tag{20}$$

$$V_C = \cos\left(\theta + \frac{2\pi}{3}\right) V_d + \sin\left(\theta + \frac{2\pi}{3}\right) V_q \tag{21}$$

$$\theta = \frac{\pi}{2} - 2\pi f t \tag{22}$$

3. DEVELOPMENT OF SOFTWARE

To ease the calculation and learning of Clarke-Park transforms, an application is developed. The application visualized the conversion of 3-phase sequence to αβ sequence, αβ sequence to 3-phase sequence, αβ sequence to dq sequence, dq sequence to αβ sequence, 3-phase sequence to dq sequence, dq sequence to 3-

phase sequence. It will be a practical tool for those who want to learn Clarke and Parke transforms, and control and modelling of the 3-phase systems. How the d and q amplitudes could affect the phase, and the system could be observed via this application. The steps of the application algorithm could be seen as below:

1. Start the program
2. Enter the values for desired transform
3. Press the "Calculate" button that is under the desired transform values to see all 3 sequences on the time domain
4. Before new calculation canvas can be cleared by pressing "Clear" button
5. Press the "Plot Reference Frames" button to see all 3 sequences on their respectable frames.
6. Press the "Close" button to come back to the previous window
7. Press the "Show Transform Formulas" button to see all transform formulas
8. Press the "Close" button to come back to the previous window
9. Exit the program

The application is developed by python programming language, for easily making the adjustments. Tkinter graphical python library is used for the graphical user interface and Matplotlib is used for plotting. The tool provides the opportunity of exploring the relationships between three-phase (abc), Clarke (αβ), and Park (dq) reference frames for the users in a highly intuitive manner. With the launch of the application, users can see the three main input panels corresponding to the three-phase system, Clarke transform, and Park transform. Each panel allows user to enter desired amplitude, frequency and phase (or dq amplitudes) values of the respective signals. After entering the values, users can generate the waveforms by pressing the "Calculate" button in each section and they can observe the change of the waveforms by changing the values [26, 27]. The GUI (graphical user interface) of the application can be seen in Figure 1.

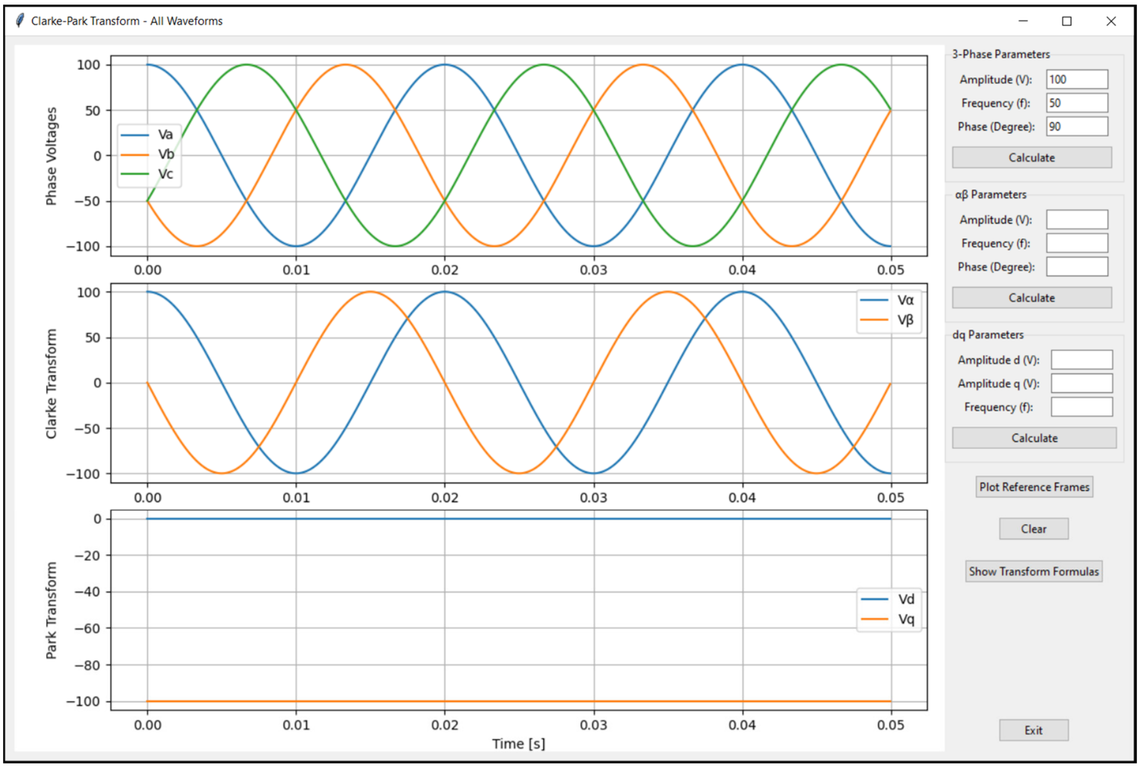

Figure 1. Software user interface

Additionally, the application provides "Plot Reference Frames" button, which opens a new window that displays the vector diagrams for the abc, αβ, and dq reference frames. This visualization aids the users to understand the transformation of the signals onto orthogonal axes, and how the d and q amplitudes, and phase value proportion works. This is a key concept in vector control and field-oriented control of AC machines. For user convenience, "Exit" buttons are added both in the main window and in the reference frame plot window, allowing for easy closure of the application or individual plots. The reference frame plot window can be seen in Figure 2. For the users those would like to see or want to remember or learn, there is “Show Transform Formulas” button. If the users press on this button, all six transform formulas will be at this window. Transform formulas window can be seen Figure 3.

The application is packaged into a standalone executable using PyInstaller, making it easily distributable to end users. The distribution package includes the main executable file and files that the main executable file used when working [28, 29]. This application is a useful tool for students, educators and engineers who wish to gain deeper understanding of and are working on electric-machine control, modelling and mathematical transformations. By allowing real-time parameter adjustment and immediate visualization, the application fills the gap between theoretical and practical concepts. This article section provides an overview of the application's development while remaining accessible to readers with a basic understanding of electrical systems and software development.

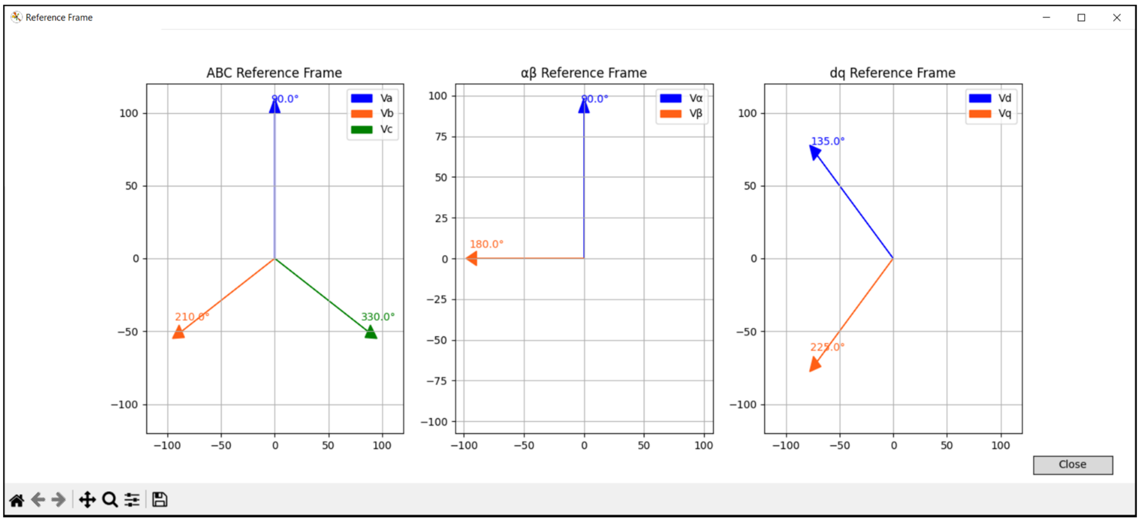

Figure 2. Reference frame window

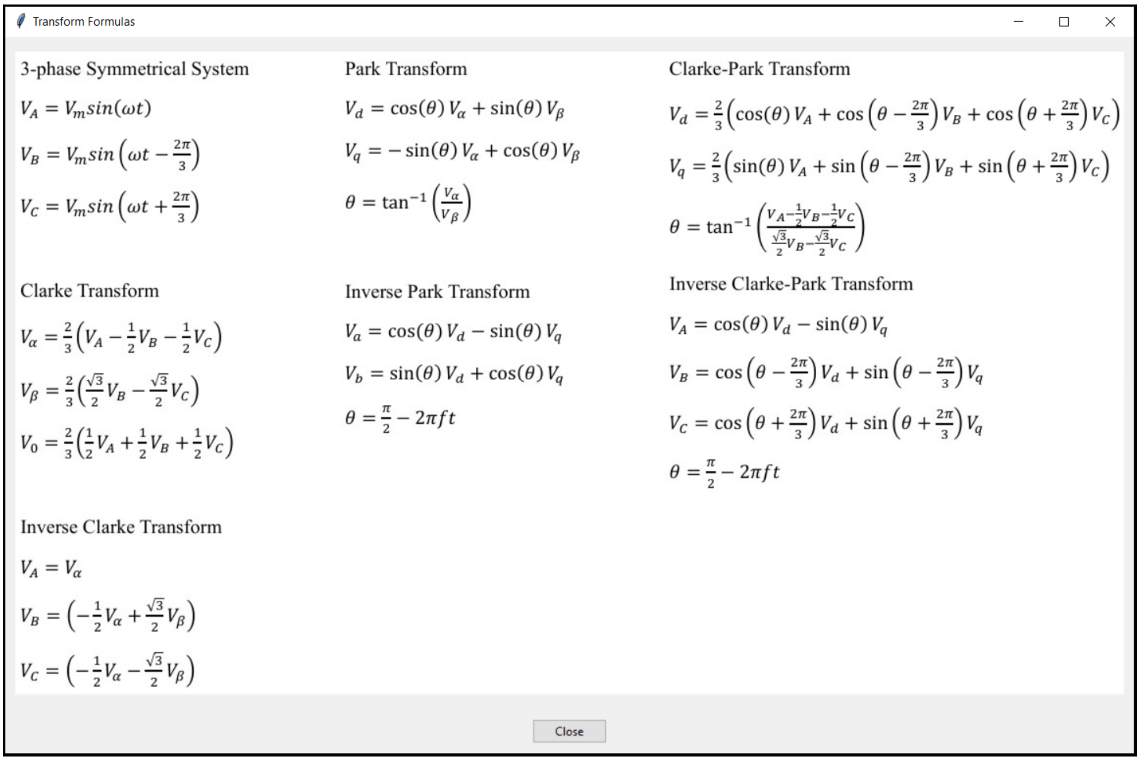

Figure 3. Transform formulas window

4. CONCLUSION

In this study, information related to motor control, Clarke and Park transforms has been given alongside the development of a user-friendly software tool that visualizes and calculates these transforms. Motor control methods can be examined in two groups: vector and scalar control. As its name suggests scalar control methods use scalar parameters such as voltage, current, frequency, pole and flux to control motor. By changing the frequency, motor speed can be controlled. Changing the frequency affects the motor torque. While voltage is constant and frequency increased, motor torque decreases. Scalar control finds optimum values for these parameters. FWC, DTC and FOC are mostly used vector control methods, but the most popular control method is FOC. It uses Clarke and Park transform to simplify the control of motor. To acquire the maximum torque, rotor flux must be orthogonal to stator flux. To achieve this state, FOC converts 3-phase amplitudes and phase to two sequence vectors (dq). This conversion has been made by using Clarke and Park transforms.

Clarke transform converts 3-phase rotational frame into 2-phase stationary frame. Park transform 2-phase stationary frame into dq referance frame. With the inverse clarke and park transforms, all three frames can be converted into each other. In the proposed application, with its interactive and dynamic plotting capabilities, understanding of how changes in system paramaters could effect the 3-phase system is enhanced. The forward and inverse transform features not only support learning but also assist the engineers in calculating clarke and park transform.

This tool provides valuable resources both educational and practical for students, educators and engineers by simplifying complex concepts through visualization. The software contributes to better understanding and more effective application for Clarke and Park transforms into 3-phase control systems and promotes deeper insight and more intuitive learning in the field of electric machine control. For the later studies, the application can be further expanded with real time data acquisition and hardware integration. These new features make it a more powerful tool for both simulation and practical implementation for 3-phase systems.

To conclude, in this study, the implementation of Clarke-Park transforms software that calculates, visualizes and converts 3 different sequences into each other is carried out. With this article and software, understanding of Clarke and Park transforms will be easier and they will be a reference point for the ones who are interested in these subjects. In order to obtain the application, it is recommended to contact the corresponding author via e-mail.

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