THE LOAD FLOW CALCULATION IN RADIAL ELECTRIC NETWORKS WITH DISTRIBUTED GENERATION UNDER UNBALANCED AND HARMONIC POLLUTED REGIME

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ABSTRACT

The growth of distributed generation (DG) which is consumer driven and not centrally planned presents a number of challenges and opportunities specific mainly to low voltage (LV) distributed networks. The growth of DG in order to meet the UK government's environmental targets for 2010 will taken into consideration for example the following LV distribution network constraints: steady-state voltage limits, voltage unbalanced limits and harmonic limits. This paper presents an algorithm developed by the authors in order to perform load flow calculation in unbalanced and harmonic polluted low voltage radial networks with distributed generation. The authors propose to model the harmonic complex quantities (a set of complex quantities corresponding to each harmonic component) through *abstract data types* with complex parameters. For harmonic polluted and unbalanced radial electric networks that include distributed generators, it was considered the backward/forward sweep with some specifications and adaptations.

Keywords: Small Scale Energy Zone, Distributed Generation, Load Flow Calculation, Unbalanced and Harmonic Polluted Operation, Object Oriented Programming.

1 INTRODUCTION

The UK government's policy on renewable energy and Combined Heat and Power (CHP) is expected to lead to a continuous increase in Distributed Generators (DG). In order to meet the government's target for 2010, approximately 10GW of additional DG will have to be connected to distribution networks. This will require the commissioning of thousands of generators of different types and sizes. SSEG is seen as an important part of the additional DG that is required to meet these targets [1]. This is because technologies such as dCHP (Domestic Combined Heat and Power units), small wind turbines and photovoltaic arrays have the potential to be adopted by many domestic and commercial load customers [2].

SSEGs are defined in Engineering Recommendation G83/1 [3] as any source of electrical energy rated up to, and including, 16 Ampere per phase, single or multi phase, 230/400 Volts ac. These generating units are most likely single-phase and are generally connected to low-voltage networks (typically 400/230V in Europe) within a domestic or light commercial property. Their single-phase nature along with the fact that their growth is consumer-driven and not centrally planned (ER G83/1's "fit and inform" principle) is likely to cause voltage unbalance. In the UK, Engineering Recommendation P29 [4] defines the acceptable level of unbalance in distribution networks and Engineering Recommendation G5/4 [5] defines the acceptable levels of the harmonics in distribution networks.

The paper presents a solution (and dedicated software) to perform load flow calculus in unbalanced and harmonic polluted low voltage radial electric networks with distributed generation using *abstract data types*.

2. SMALL SCALE ENERGY ZONE

The value of SSEGs can be defined as being determined by the following factors:

- The revenue streams that can be achieved.
- The degree to which they can participate in ancillary services market.
- The environmental impact that can be achieved.
- The ability to contribute to deferral/avoidance of network reinforcements.

When considering a single SSEG it is difficult to see how they can make significant impacts in any of the four areas listed above. Groups of SSEGs will be considered within a small scale energy zone SSEZ. In this research a SSEZ is defined as a controllable section of LV network containing a mixture of SSEGs, distributed storage and load, Figure 1. These elements are controlled in order to increase the value of SSEGs and achieve a local energy balance [6].

A SSEZ could be a housing estate, an industrial estate or an office block. The SSEZs network is responsible for servicing the needs of its consumers, ensuring a quality of supply and the interface with the local electricity utility.

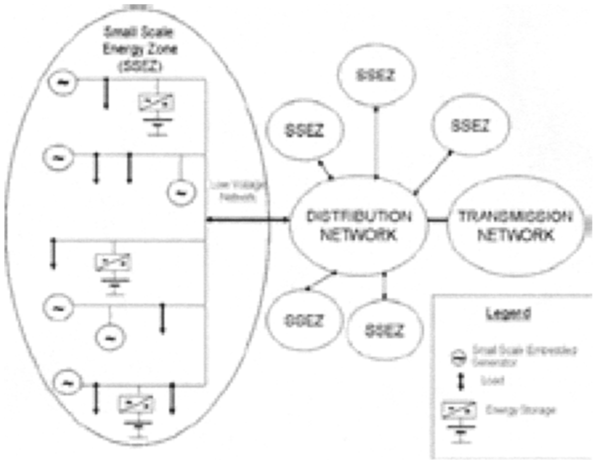

Figure 1 Small Scale Energy Zone

3 ELECTRIC QUANTITIES AS ABSTRACT DATA TYPES

In the case of harmonic polluted electrical networks, the load flow calculation consists in the determination of steady state quantities for *each harmonic component* at a time. On the other hand, the load flow calculation for unbalanced/asymmetrical electrical networks consists in the determination of steady state quantities for *each phase* at a time. The theoretical relationships proposed in literature are difficult to be implemented in harmonic polluted and unbalanced/asymmetric complex systems.

Besides, the data types existing in the numbers theory, the high level programming languages allow the definition of new artificial data types, for instance *abstract data types*. The term *type of data* designates a *set of values* (the domain of type) and *a set of operations* that can be performed with these values. As an example, it can be considered data belonging to the real numbers set (the domain of type). In this case, they can perform arithmetical operations with another real number (operations among the same data types), arithmetical operations with an integer number (operations among the specified type of data and another type), and the extraction of integer part (operation applied to the data type itself).

To specify a concrete *abstract data type*, it is necessary to indicate the two elements of the type, i.e. the domain and the operations:

- *the domain* is specified as a mathematical set;
- *an operation* is described by its mathematical definition.

3.1 Complex quantities as abstract data types

Complex numbers are very often used in electrical engineering. They have the following characteristics:

1) Domain: The domain of these numbers is indicated by C and is specified as:

$$C = \{(a,b) \mid a,b \in R\} \qquad (1)$$

2) Operations Set: In the complex numbers set, the following operations are defined:

– for any two quantities $v_1, v_2 \in C$, it is possible to determinate the quantity $v \in C$, with parameters a_e and b_e, defined through:

Addition: $v = v_1 + v_2$,

where: $a_e = a_1 + a_2, \quad b_e = b_1 + b_2 \qquad (2)$

Similarly, it is possible to define the operations: subtraction (-), multiplication (*) and division (/).

– for any quantity $v \in C$, it is possible to determinate the subsequent quantities:

Conjugate: $v_1 \in C$ defined through $v_1 = v^*$, with parameters a_e and b_e calculated as follows:

$$a_e = a_1 \quad b_e = -b_1 \qquad (3)$$

Module: $r \in R$ defined by $r = |v|$, calculated as: $r = |v| = \sqrt{a^2 + b^2} \qquad (4)$

Angle: $\theta \in R$ defined by $\theta = Angle(v)$, calculated as: $\theta = Angle(v) = atg\frac{b}{a} \qquad (5)$

3.2 Harmonic complex quantities as abstract data types

A "harmonic complex" number may represent many non-sinusoidal physical quantities, namely voltage, current, impedance etc [8].

1) Domain: The domain of these quantities (the harmonic complex numbers) is denoted by HC and specified as:

$$HC = \{(v_1, v_2, \ldots, v_i) \mid v_i \in C; \ i = \overline{1,n}; \ n \in N^*\} \qquad (6)$$

2) Operations Set: The following operations are defined in this set:

– for any two quantities $A, B \in HC$, it is possible to determinate the quantity $C \in HC$, with parameters (c_1, c_2, ..., c_n), defined through:

Addition: $C = A + B$, where: $c_i = a_i + b_i; \ i = \overline{1,n}; \ n \in N^* \qquad (7)$

Similarly, it is possible to define the operations: subtraction (-), multiplication (*) and division (/).

– for any quantity $A \in HC$, it is possible to determinate the quantity $r \in R$ defined as:

Module: $r = |A|$, calculated as:

$$r = |A| = \sqrt{\sum_{i=1}^{n} |a_i|^2}; \qquad n \in N^* \tag{8}$$

Dross: $r = Dross(A)$, calculated as:

$$r = Dross(A) = \sqrt{\sum_{i=2}^{n} |a_i|^2}; \qquad n \in N^* \tag{9}$$

Total harmonic distortion: $r = THD(A)$, calculated as:

$$r = THD(A) = \frac{Dross(A)}{|a_1|} \cdot 100 \tag{10}$$

– for any quantity $A \in HC$, it is possible to determinate the quantity $B \in HC$, with parameters ($b_1, b_2, \ldots, b_n$), defined through:

Conjugate: $B = A^*$, calculated according to:

$$b_i = a_i^*; \quad i = \overline{1,n}; \quad n \in N^* \tag{11}$$

Weight: $B = Weight(A)$, calculated according to

$$|b_i| = \frac{|a_i|}{|a_1|} \qquad i = \overline{1,n}; \quad n \in N^* \tag{12}$$

$$Angle(b_i) = Angle(a_i)$$

Equivalent vector: $B = \overline{A}$, calculated according to:

$$B = A + A \cdot a^2 + A \cdot a \tag{13}$$

where $a = (a_1, a_1^2, \ldots, a_1^i); \; i = \overline{1,n}; \; n \in N^*$ is defined as '*harmonic rotation factor*' and $a_1\left(-\frac{1}{2}, \frac{\sqrt{3}}{2}\right)$ is the rotation factor for the fundamental harmonic component case;

– for any two quantities $A \in HC$, $|B| \in R$ it is possible to determinate the quantity $B \in HC$, with parameters ($b_1, b_2, \ldots, b_n$), defined through:

RMS (root mean squares): $B = RMS(A)$, calculated according to:

$$|b_1| = \frac{|B|}{|A|}$$

$$|b_i| = |b_1| \cdot |a_i| \qquad i = \overline{1,n}; \quad n \in N^* \tag{14}$$

$$Angle(b_i) = Angle(a_i)$$

3.3 Harmonic complex three phase quantities as abstract data types

1) Domain: The domain of these quantities (the complex three-phase numbers) is denoted with *HCT* and is specified as:

$$HCT = \{(r, s, t) \mid r, s, t \in HC\} \tag{15}$$

2) Operations Set: The following operations are defined in this set:

– for any two quantities $v_1, v_2 \in HCT$, it is possible to determinate the quantity $v \in HCT$, with parameters r_e, s_e and t_e, defined through:

Addition: $v = v_1 + v_2$,

$$\text{where: } r_e = r_1 + r_2 \quad s_e = s_1 + s_2 \quad t_e = t_1 + t_2 \tag{16}$$

Similarly, it is possible to define the operations: subtraction (-), multiplication (*) and division (/).

– for any quantity $v_1 \in HCT$, it is possible to determinate the quantity $v \in HCT$ with parameters r_e, s_e and t_e defined through:

Symmetrical components: $v = SC(v_1)$, where:

$$r_e = \frac{1}{3} \cdot (r + s + t)$$

$$s_e = \frac{1}{3} \cdot (r + s \cdot a + t \cdot a^2) \tag{17}$$

$$t_e = \frac{1}{3} \cdot (r + s \cdot a^2 + t \cdot a)$$

where r_e represents zero sequence component,
s_e represents positive sequence component
t_e represents negative sequence component.

The following parameters can be also easily determined:

Unbalance factor:

$$k^- = |t_e| / |s_e| \tag{18}$$

Asymmetry factor:

$$k^0 = |r_e| / |s_e| \tag{19}$$

– for any quantity $v_1 \in HCT$ it is possible to determinate the quantity $hc \in HC$ defined through:

Equivalent vector: $hc = \overline{v_1}$,

$$\text{calculated as: } hc = r_1 + s_1 + t_1 \tag{20}$$

The authors propose to model the harmonic complex quantities (a set of complex quantities corresponding to each harmonic component) through *abstract data types* with complex parameters ($\underline{x}_1, \underline{x}_2, \ldots, \underline{x}_n$). Similarly, it is proposed to model the three-phase harmonic complex quantities (symmetrical, asymmetrical, balanced or unbalanced) through *abstract data types* with three harmonic complex parameters (*r, s, t*), among these parameters, some operations are defined. By implementing this model, all three-phase harmonic quantities will be considered as "harmonic complex three-phase" objects. As a result, electrical engineering laws, like Ohm or Kirchhoff, are reduced to simplified expressions corresponding to fundamental harmonic component single-phase case.

4 LOAD FLOW CALCULATION FOR ELECTRIC NETWORKS

The load flow calculation for electric networks consists in the determination of steady state quantities associated to its elements. The type of network selected for this research is a radial LV distribution system with the characteristics of an urban configuration with multiple SSEZs connected. Clearly, urban networks represent areas with relatively high load densities with large numbers of customers.

4.1 Adaptation of backward/forward sweep algorithm for unbalanced and harmonic polluted radial electric networks

In this case, it was taken into consideration two types of nodes:

- one source node (infinite bus), to which the specified quantities are the components of voltage, and the unknown quantities are the components of loads (powers, currents);
- some load nodes, to which the specified quantities are the loads (constant powers, constant currents, constant impedances/admittances or a combination of the above), and the unknown quantities are the components of voltage.

The load flow calculation can be performed using a specific method, known as the *backward/forward sweep*. This method consists of two steps [9]:

- *Backward sweep,* where, starting from the end nodes and going towards the source node, and using the Kirchhoff's current law, the current at each load node, as well as the current flowing through its ingoing branch, are calculated;
- *Forward sweep,* where, starting in the opposite direction, from the source node S (whose constant voltage is taken as reference) and going towards the end nodes, using the Ohm's law, the voltage drop on each branch, as well as the voltage at each load node, are calculated.

In harmonic polluted and/or unbalanced power systems, the above-proposed models can be introduced. Accordingly, the load flow calculation algorithm using the backward/forward sweep consists in the following steps:

a. Ordering the network (indexing the ingoing node and branch for each load node) and setting the voltages at the load nodes to the value of the source node (S) phase voltage. In this first step, the voltage system is considered as symmetrical and sinusoidal:

$$U_k^{(0)} = U_S, k = 1,2,\ldots,n, k \neq S \qquad (21)$$

where $U_k \in HCT$;

b. Setting the initial iteration index: $p = 1$;

c. *Backward sweep:* crossing the network from the end nodes towards the source node and performing the following operations:

c.1 Calculation of the current at the node k by using the expression of the load power given by:

if k is non-liner

$$[I_k^{(p)}]_{phase} = RMS([IP_k]_{phase}) \qquad (22)$$

where:

$[I_k^{(p)}]_{phase}, [IP_k]_{phase} \in HC$

$|[I_k^{(p)}]_{phase}| = \dfrac{|[S_k^*]_{phase}|}{|[U_k^{(p)*}]_{phase}|}$

r.m.s. value of the current;

$phase = r, s, t$

else

$$I_k^{(p)} = \frac{S_k^*}{U_k^{*(p-1)}} \qquad (23)$$

where $I_k^{(p)}, S_k^* \in HTC$

c.2 Calculation of the current flowing through the branch ingoing to node k:

$$I_{ik}^{(p)} = I_k^{(p)} + \sum_{j \in Next(k)} I_{kj}^{(p)} \qquad (24)$$

if *connection* = Y

$$I_{ikN}^{(p)} = \bar{I}_{ik}^{(p)} \qquad (25)$$

if *connection* = Δ

$$I_{ikN}^{(p)} = \sum_{j \in Next(k)} I_{kjN}^{(p)} \qquad (26)$$

where: i is the index of the node up stream to the node k;
Next(k) is the set of nodes next to the node k;

d. *Forward sweep:* the calculation of voltages at the nodes, crossing the network from the source node towards the end nodes. For the in progress iteration *p,* considering the crossing direction of a branch from the node *i* towards node *k,* the calculation is performed as following:

d.1 Calculation of the voltage drop on the *i* - *k* branch:

$$\Delta U_{ik}^{(p)} = Z_{ik} \cdot I_{ik}^{(p)} + Z_{ikN} \cdot I_{ikN}^{p} \tag{27}$$

where: $Z_{ik} \in HCT$;

with $Z_{ikN} \in HC$ - harmonic impedance of neutral conductor;

d.2. Calculation of the voltage at the node *k:*

$$U_{k}^{(p)} = U_{i}^{(p)} - \Delta U_{ik}^{(p)} \tag{28}$$

e. Calculation of the power injected into the network by the source node:

$$S_{S}^{(p)} = U_{S} \cdot \sum_{i \in Next(S)} I_{Sj}^{*(p)} \tag{29}$$

f. If $p > 1$ and $|\overline{S}_S^{(p)} - \overline{S}_S^{(p-1)}| \le \varepsilon_S$ then go to the next step, else update $p = p + 1$ and go to step c.

g. Ca1culation of power losses through the network branches.

4.2 Adaptation of backward/forward sweep algorithm for unbalanced and harmonic polluted radial electric networks with DG

Distributed generators can be classified:

- generators which provide *constant powers* (*P_1Q_1 nodes*), to which the specified quantities are the constant powers and the unknown quantities are the components of voltage;
- generators which provide *constant active powers* and *constant modules of voltages* (*P_1U_1 nodes*), to which the specified quantities are the active power and module of voltage, and the unknown quantities are the reactive power and the angle (phase) of voltage. These sources can generate active power and sometimes can generate or consume reactive power, having the possibility to maintain the nodal voltage at a set value by means of an automatic voltage regulator [9].

For harmonic polluted and unbalanced radial electric networks that include DG, it was considered the backward/forward sweep with some specifications and adaptations. The algorithm is presented in the following:

1. Initialise the iterative step $p = 0$ and establish the initial value of the (generated) reactive power for every P_1U_1 nodes: $Q_{g,k}^{(0)} = 0$;

2. Update the iterative step $p = p + 1$;

3. Perform load flow calculation by *backward/forward sweep*;

4. If for each node *k* (P_1U_1 type)

$$\| \, [U_k^{(p)}]_{phase} \, | - | \, [U_k^{specified}]_{phase} \, \| \le \varepsilon_U$$

Or $Q_{1g,k}^{calc} = Q_{1g,k}^{\min}$ or $Q_{1g,k}^{calc} = Q_{1g,k}^{\max}$

where $phase = r, s, t$, the iterative process stops;

5. Calculate the generated reactive power $Q_{1g,k}^{calc}$ necessary to achieve the specified voltage $U_k^{specified}$ at a node *k* (the P_1U_1 nodes), e.g. using the secant method:

$$Q_{1g,k}^{calc} = Q_{1g,k}^{(p-1)} + \frac{Q_{1g,k}^{(p-1)} - Q_{1g,k}^{(p-2)}}{|U_{1k}^{(p-1)}| - |U_{1k}^{(p-2)}|} \left(|U_{1k}^{(p)}| - |U_{1k}^{specified}| \right) \tag{30}$$

$$\begin{cases} if \ \left(Q_{1g,k}^{\min} \le Q_{1g,k}^{calc} \le Q_{1g,k}^{\max} \right) & then \ Q_{1g,k}^{(p)} = Q_{1g,k}^{calc} \\ if \ \left(Q_{1g,k}^{calc} < Q_{1g,k}^{\min} \right) & then \ Q_{1g,k}^{(p)} = Q_{1g,k}^{\min} \\ if \ \left(Q_{1g,k}^{calc} > Q_{1g,k}^{\max} \right) & then \ Q_{1g,k}^{(p)} = Q_{1g,k}^{\max} \end{cases} \tag{31}$$

6. Go to step *2*.

5. APPLICATION

The authors developed an original program, named *OBtriarm*, dedicated to mathematical operations with harmonic complex three-phase quantities. Implemented with a *GUI* (*Graphic User Interface*) technology, the program allows an extreme easiness in the use. An example of how the developed software can be used is presented.

In the program are introduced eleven harmonic complex three-phase objects, named **A**, **B**, **C**, ..., **K**. For each object are defined:

- one *location* for writing relationships among the harmonic complex quantities (objects);
- a *table* with modules of 50 harmonic components for each phase at a time (r, s, t);
- a *table* with angles of 50 harmonic components for each phase at a time (r, s, t);
- a *check box* (HC) to convert the object in *harmonic complex* type.

Any harmonic complex three-phase quantity is introduced (as input data) through ***Input / Output*** panel and is attached to an object making a 'click' on '<<' button concordant to symbol of the object (Figure 2). The results are obtained making a 'click' on '***RUN***' button and appear in the two tables with module and angles of harmonic components for each phase at a time. Any phase of an object can be also graphically viewed in ***Input/Output*** panel making a 'click' on the '>>' button concordant to symbol of the object. Making a 'click' on the '*' button concordant to symbol of an object, in the '***Characteristic quantities'*** panel, the following data are displayed: RMS value, THD, the dross (*Xd*) for each phase at a time and the unbalance and asymmetry factors.

The proposed software program was used to calculate the voltage drops in a harmonic polluted (line currents contain two harmonic components of order 3 and 5) and unbalanced electric power line in a Small Scale Energy Zone. To solve this particular problem, only the following objects are necessary:

- **A** – harmonic content of line currents on each phase (currents are unbalanced), (A);
- **B** – harmonic line impedances for each phase (impedances are balanced), (Ω);
- **C** – harmonic voltage drops on the phases, (V);
- **D** – harmonic currents on the neutral conductor, corresponding to the geometrical sum of the line currents - equivalent vector, (A);
- **E** –harmonic impedance of neutral conductor, (Ω);
- **F** – harmonic voltage drops on the neutral conductor, (V);
- **G** – total voltage drop on the power line, (V).

Figure 2 presents the results for this particular case. All information is displayed in different dedicated windows; for example, the window '***Characteristic quantity'*** contains the essential attributes of the object *A*. As Figure 2 displays only the data for the phase 'r', in the case of harmonic three-phase complex objects *A*, *C* and *G*, data for phases 's' and 't' are presented in Table 1.

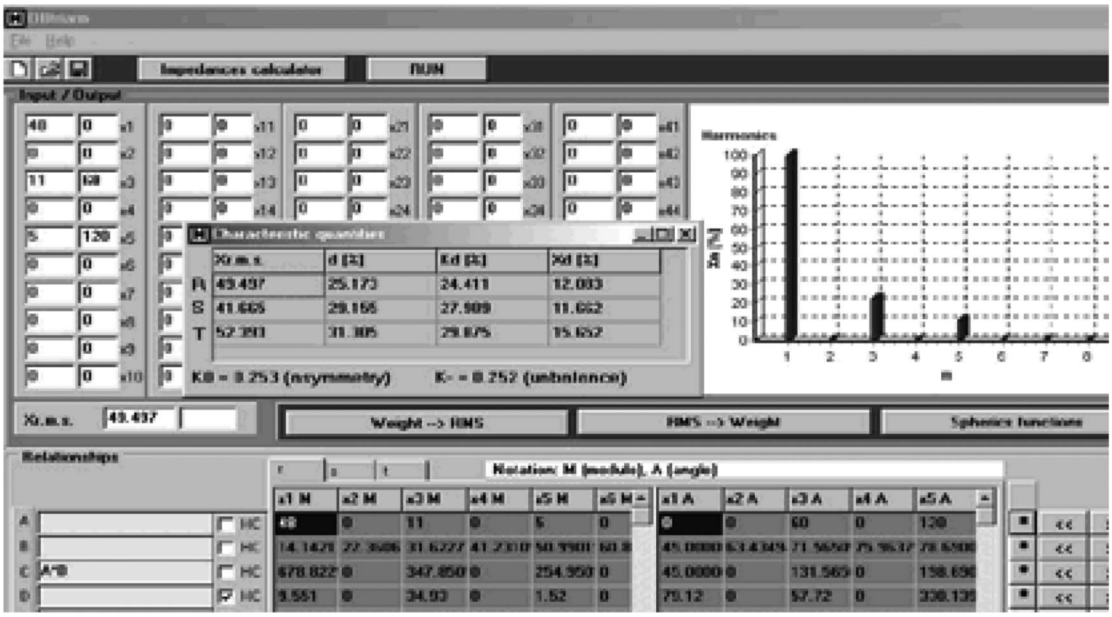

Figure 2 Sample of the results obtained with Obtriarm program

Table 1: Data for Phases 'S' and 'T'

Object	Phase	Harmonic order					
		1		3		5	
		M	A	M	A	M	A
A	s	40	238	10	52	6	238
	t	50	120	14	60	7	360
C	s	565.6	283	316.2	123.5	305.9	316.6
	t	707	165	442.7	131.5	356.9	78.6
G	s	596.6	290.5	894.3	122.9	271.6	312.7
	t	739.6	171	1017.8	126.5	321.8	75.5
Legend: M (module), A (angle)							

6. CONCLUSIONS

With the continually increasing number of single-phase-connected SSEGs, voltage unbalance has the potential to become a serious concern for Distribution Network Operators. The fact that their growth is consumer-driven and not centrally planned (ER G83/1's 'fit and inform' principle) render the risk of voltage unbalance even greater.

The paper presents an original solution to perform calculus with harmonic complex three-phase quantities by using *abstract data types*. Related mathematical models for *complex abstract data type*, *harmonic complex abstract data type* and *harmonic complex three-phase abstract data type* are developed. These modules can be used in any program written in *C++* language for all calculus with complex numbers, harmonic complex numbers or harmonic complex three-phase numbers. The structures were implemented as objects in the software which allows manipulating complex, harmonic complex and harmonic complex three-phase quantities by simply using common arithmetic operators. This software product is very useful as majority of electrical systems are operated in harmonic distorted and unbalanced regimes.

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