Reusing Three-Phase Power-Flow Object Components for Unbalanced Harmonic Analysis

Khalid M. Nor, *SMIEEE*, L. W. Jeun, M. Abdel-Akher, and A. H. Abdul-Rashid

Abstract —**In this paper, the harmonic penetration method is developed as a component-based application. The direct nodal voltage harmonic solution is developed as an independent software component and then integrated with existing three-phase power-flow software components. The harmonic solution reuses many facilities available in the fundamental frequency power-flow object components. The nonlinear devices such as six pulse converters are modeled as entity objects and inherited from the basic object-oriented power-system device model at fundamental frequency. Also, the linear solver also is reused form the power-flow component library. The application of object components shows that the development of complicated algorithms becomes easy due to the high code reusability.**

Index Terms- three-phase power-flow, three-phase harmonic power-flow, object components, and symmetrical networks

I. INTRODUCTION

HARMONIC POWER-FLOW STUDIES have a growing interest due to the increase of nonlinear devices connected to the power system network. One part of the harmonic power-flow would include the harmonic simulation methods which are used to calculate the harmonic current injected by nonlinear devices. The harmonic simulation methods can be categorized into two main categories [1]:

i. The time domain analysis. In this technique, numerical integration is used to solve a set of nonlinear differential equations describing the system. The technique requires a detailed representation of all devices and hence the solution time can be very high.

ii. The frequency domain analysis. In this technique, detailed representations of nonlinear load are adopted. The approach is more accurate than ideal current or voltage representation.

The frequency domain methods for harmonic analysis can be also classified into categories according to the reformulation of the conventional power-flow at fundamental frequency [2]. One of the harmonic analysis methods is the harmonic penetration analysis. The harmonic penetration (HP) is based on the direct voltage nodal solution which uses the calculated harmonic admittance matrix and the injected harmonic current to solve for the harmonic voltages.

Component technology based on OOP allows the development of the decomposed algorithms as proposed in our previous work [3], [4] as independent object components. The fundamental power-flow analysis [3], [4] has been modeled based on rigorous object-oriented approach according to the classification of objects proposed by Jacobson [5]. There are two main types of objects have been introduced in [3]:-

i. The power system devices: are modeled as entity objects. This category of objects represents the physical network and developed as a standalone class hierarchy using object-oriented programming (OOP).
ii. The solution algorithms: are modeled as control objects. These control objects represents the power-flow solution algorithms such as linear solver, Newton-Raphson, fast-decoupled etc. The control objects are developed as independent software components based on object-oriented design.

In this paper, an extension for our previous work [3], [4], [6] is proposed to develop unbalanced harmonic power-flow application using HP technique. The HP algorithm requires the solution of the fundamental frequency network that is included by reusing three-phase power-flow object components [4]. Consequently, only the solution for harmonics is developed using the nodal voltage method. The solution of harmonics is developed and encapsulated in a new object component. In addition, new classes are inherited from the basic power system model class library to model the nonlinear devices. The HP solution is obtained by integrating the three-phase power-flow object components with the object component of the nodal voltage solution for harmonics in a functioning component-based development (CBD) application.

II. UNBALANCED HARMONIC PENETRATION

Harmonic penetration method assumes no interaction between the network and the nonlinear devices which means that the harmonic voltages have no influence on the nonlinear devices. The injected harmonic current by the nonlinear devices is caused solely by its fundamental voltage and it is not affected by the harmonic voltages. The harmonic penetration flow chart is shown in Fig. 1 whereas the formulation is given in Table I for an n bus system.

The network harmonic admittance matrix can be obtained by modifying the fundamental network admittance matrix. The harmonic order factor has to be taken into account for the reactance and susceptance.

$$Y_i^h = f_i(Y_i, h) \qquad (1)$$

where f_i is a function which depends on the harmonic admittance model.

Therefore, (1) is used to solve for harmonic voltage using the harmonic penetration method as follows:

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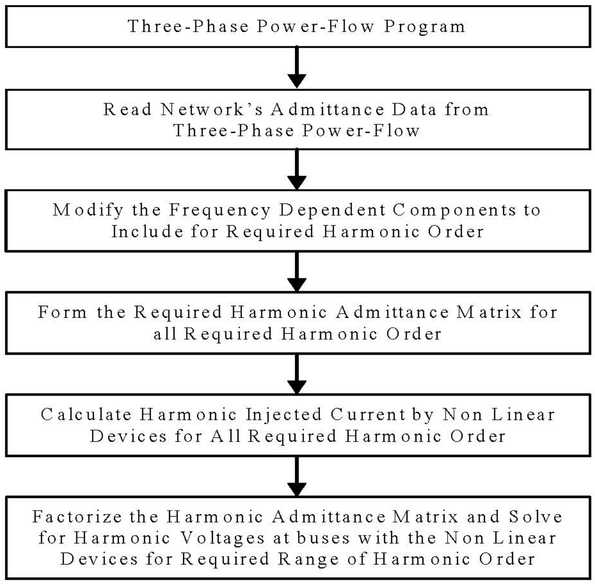

Fig. 1 Flow chart for harmonic penetration

TABLE I
HARMONIC PENETRATION FORMULATION

	Bus	Data	Unknown
Conventional Power-Flow (modified)	S	V_1^1	none
	PV	P_i , U_i	V_i^1
	PQ	P_i , Q_i	V_i^1
	NLD	B_i^1 ,... B_i^r	V_i^1 , β_i^1 ... β_i^r
Voltage Nodal Method	S	X_1	V_1^h
	PV	X_i	V_i^h
	PQ	Y_i^h	V_i^h
	NLD	I_j^h	V_i^h

Where B_i^j and β_i^j with j=1,.....r are generic Nonlinear Device Data and parameters respectively. X_1 and X_i with i=2,.....g are the reactances of the slack and PV bus generators at fundamental frequency.

$$I_B^h = Y_{Bm}^h . U_B^h \tag{2}$$

Where I_B^h is the injected harmonic current at each nonlinear bus is, Y_{Bm}^h is the modified harmonic admittance matrix, and U_B^h is the harmonic voltage to be solved

For the purpose of this study, the injected harmonic current at buses connected to nonlinear device can be represented as a percentage of the fundamental current. A few models of nonlinear device have been obtained from [7-9] which includes six pulse converter, adjustable speed drive, fluorescent light, television, and incandescent light dimmer.

III. THREE-PHASE POWER-FLOW OBJECT COMPONENTS

The three-phase power-flow program is developed using component technology and object oriented programming and implemented using Borland C++Builder environment. The power-flow solution is established using sequence decoupled networks and has been reported in [4, 10]. The algorithms utilized Sequence Newton-Raphson (SNR) and Sequence Fast-Decoupled (SFD) methods.

The two unbalanced power-flow algorithms are developed as two independent software components and they developed by reusing balanced power-flow Newton-Raphson (NR) and Fast-Decoupled (FD) methods [3]. The component diagram is shown in Fig. 2. The figure exhibits two components for balanced power-flow, NR and FD, two components for unbalanced power-flow, SNR and SFD, and one component for the sparse linear solver. The figure also shows two CBD applications for the solution of both balanced and unbalanced power-flow analysis.

IV. DEVELOPMENT OF THE NODAL VOLTAGE METHOD OBJECT COMPONENT

A. *Extension of the basic power system model*

The power system model has long live software cycle. The model is usually seldom to be subject to frequent changes. The power system model was modeled as a concrete objects encapsulates the primitive data for each device. Fig. 3 shows the basic power system class library that represents the real elements of an electrical network. The basic class library (object-oriented power system model) was used in the development of both balanced power-flow proposed in [3] and the three-phase power-flow [4], [10]. This library has been extended in this paper for modeling the nonlinear devices required for harmonic analysis. Both the basic library and the new classes for nonlinear devices are used for developing the nodal voltage solution algorithm as an object component.

B. *Nodal voltage harmonic solution component*

The nodal voltage method requires the formulation of the system admittance matrices at each harmonic up to any desired order as given in the flowchart shown in Fig. 2. The data structure of the admittance matrix at fundamental frequency network is basically created in the fundamental frequency three-power power-flow. Therefore, only modification for this structure is required to update the values of the sequence network matrices at each harmonic.

In traditional programming techniques, it is very difficult to pass variables in manageable way due to the strong coupling between the code of the fundamental frequency power-flow and the nodal voltage solution of the harmonics. However in this paper, the algorithms are created as object components, the development of the new algorithms can be developed without (or minimum) coupling between the newly developed codes and the old codes. This is because the software components are designed with well established interfaces that enable the users to exchange the data or use the methods in easy and efficient way.

The nodal voltage solution components reuse the basic power system library as well as the new devices classes created especially for harmonic solution as given in Fig. 3. The statement to create the nodal voltage solution component using Borland C++Builder, named as TUHP, is

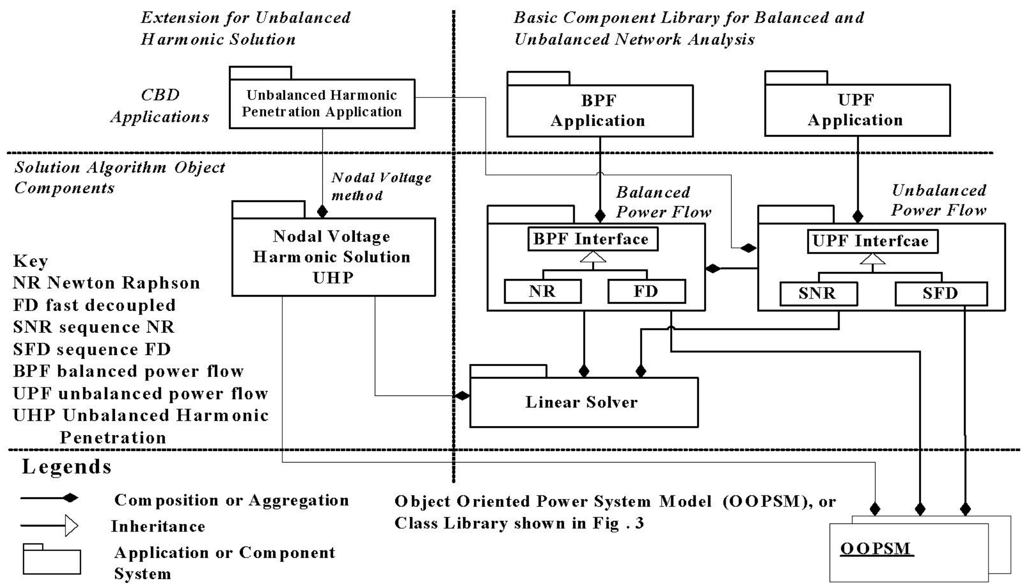

Fig. 2 Extension of the basic power-flow components for unbalanced harmonic solution

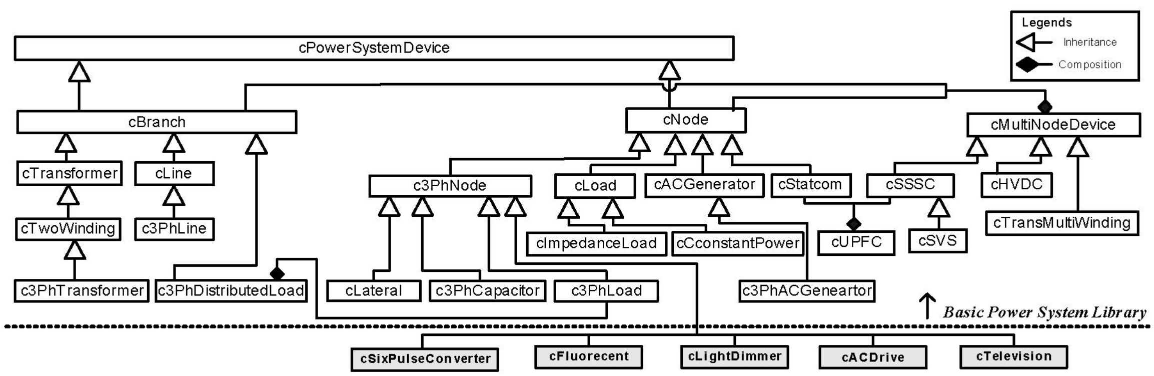

Fig. 3 Extension of the basic power system model

as follows:

```
class PACKAGE TUHP: public TComponent
```

The letters in TUHP hold to:

- **T** refers to the object or the class is developed as component similar to the letter "c" which refers to a class in the OOP design such as given in Fig. 3,
- **U** refers to the word Unbalanced,
- **H** refers to the word Harmonic, and
- **P** refers to the word Penetration.

The class TComponent is the common ancestor of all C++Builder components. The component TUHP contains the definition for the power system model which is required in the solution process in the nodal voltage method. The power system model includes objects for both three-phase devices in the basic library as well as the nonlinear devices that required for calculation the current injection given by (2). Therefore, the following objects are defined in the private part of the components:

```
private:
c3PHNode *ThreePhaseBus;
c3PHLoad *ThreePhaseLoad;
cSixPulseConverter *SPConverter;
cASDrive *ASD;
cFluorescent *Fluorescent;
cTelevision *TCR;
cLightDimmer *DIM;
⋮
```

In addition, object components are reused from the three-phase power-flow package for both the admittance matrix data structure and for the linear solver and they are declared in the private part of the components as follows:

```
TMatriceComplex *HarmMatriceComplex;
TAdmittanceMatrix *HarmAdmittanceMatrix;
```

In the public part of the components which is called as the component interface, interface methods are developed to exchange data or execute methods that solve for harmonics. Sample of the methods that have been developed in the interface are as follows:

```
public:
void AddSixPulseConverter(...);
void AddAdjustableSpeedDrive(...);
void AddTelevision(...);
void AddFluorescent(...);
void AddLightDimmer(...);
void DevelopHarmAdmittanceMatrix(...);
void SolveHarmVoltage(...);
void PrintHarmVoltage(...);
void CalculateVoltageTHD(...);
void Set3PHLoad(c3PHLoad *param);
void Set3PHBus(c3PHNode *param);
c3PHLoad *Get3PHLoad();
c3PHNode *Get3PHBus();
```

The TUHP components can solve for harmonics up to

TABLE II
MEASURE FOR REUSABILITY IN HARMONIC PENETRATION DEVELOPMENT

Reusability	Power System Model (Classes)	Solution Algorithms (Components)
Composition	2	4
Inheritance	6	-
Scratch	-	1
%Reuse	25% composition 75% Inheritance	80% composition 20% Scratch

any order and for systems with any number of busses. However, the component cannot run individually since it cannot solve for the fundamental three-phase voltage. Therefore it is required to be integrated with the three-phase power-flow object components for the whole harmonic solution.

V. HARMONIC PENETRATION COMPONENT-BASED APPLICATION

The component of the nodal voltage solution for harmonics is integrated with the unbalanced power flow components SNR and SFD in CBD application as shown in Fig. 2. The figure exhibits that there are several components are sharing in more than application or components system. The declaration of object components inside the harmonic CBD application is as follows:

```
if (choise==1)
LoadFlow=new TSequenceNewtonRaphson(NULL);
if (choise==2)
LoadFlow=new TSequenceFastDecoupled(NULL);
TUHarmFlow *HarmFlow=new TUHP(NULL);
  ⋮
LoadFlow->Add3PHBus(...);
LoadFlow->Add3PH Geneartor(...);
LoadFlow->Add3PH Load(...);
LoadFlow->Add3PH Transformer(...);
LoadFlow->AddLineConfiguration(...);
LoadFlow->AddSwitch(...);
LoadFlow->Add3PHLine(...);
LoadFlow->Add3PHCapacitor(...);
  ⋮
LoadFlow->Calculate();
  ⋮
HarmFlow->BRANCH_TOTAL=LoadFlow->BRANCH_TOTAl;
HarmFlow->BUS_TOTAL=LoadFlow->BUS_TOTAl;
HarmFlow->Set3PHBus(LoadFlow->Get3PHBus());
HarmFlow->Set3PH Load(LoadFlow->Get3PHLoad());
  ⋮
HarmFlow->AddSixPulseConverter(...);
HarmFlow->AddAdjustableSpeedDrive(...);
HarmFlow-SolveHarmVoltage(MaximumHarmonicOrder);
  ⋮
```

Since there are two methods for the unbalanced power-flow, the user can choose which method to solve the fundamental frequency power-flow. The object LoadFlow is declared either to be as instant of the component SNR or SFD. The required data is supplied to the LoadFlow object by its interface AddObject (). After all required network data is supplied to the LoadFlow object, the fundamental frequency network can be solved by dispatching the interface method Calculate(). Many data available inside the object LoadFlow can be transferred to the object HarmFlow by using the interface of both the components such as the busbar data, load data, the admittance matrix data structure.

The harmonic solution requires the data of the nonlinear devices. This data is supplied to the object HarmFlow by its interface AddObject(). After all the data is supplied to the object HarmFlow, the calculation is performed by dispatching the interface method SolveHarmVoltage(). The harmonic admittance matrix is established and factorized using the sparse linear solver. These calculations are hidden from the components user since it is encapsulated inside the private part of the object HarmFlow.

VI. RESULTS AND DISCUSSIONS

The objective of this paper is more concerning about the development of the harmonic power-flow solution. The results presented here will discuss the reuse issue. Besides, a numerical example of solving the unbalanced 24-bus system [11] is given when nonlinear devices is existing in the network.

A. *Measure of Reuse*

The measure of reuse is performed by counting classes that have been created based on inheritance, composition, or developed from scratch. The measure of class and component reuse is summarized in Table II. Firstly, in the power system model that representing the real devices of the network, there is 6 classes are inherited form the basic power system library where there are two classes are reused based on composition. Regarding to the solution algorithms, there are four components are reused. They are two components for unbalanced power-flow, one component for the admittance matrix, and one component for linear solver.

In addition to high reusability, the component is reused without additional knowledge about the algorithm encapsulated inside it. This is because the component is designed with clear interface based on the network data which is well known for power engineers. On the other hand, the complicated algorithm formulation is hidden inside private or the protected part of the components.

B. *Example of Numerical Results*

The harmonic power-flow analysis CBD application has been tested using the 24-bus to obtain or calculate the harmonic voltage distortion for all buses for the following cases:

Case 1: Harmonic voltage due to few connected nonlinear devices.

Case 2: Harmonic voltage due to unbalanced loading demand.

In the first case, when there are few nonlinear devices connected in the 24-bus test system where Six Pulse Converters are connected at bus ID 32, 41 and 45 in the 24-bus test system with 50% of the connected bus total load, the result shows more total harmonic distortion for voltage at all buses in the system as shown in Fig. 4.

If there is only one nonlinear device is connected to the 24-bus test system, the harmonic distortion is lower. This is because when more nonlinear devices are connected to the network's buses, the harmonic voltage distortion will increase at all buses in the network. This is due to the fact that the total or amount of harmonic injected current into the network has been increased and thus increasing the harmonic voltage distortion in the network's buses.

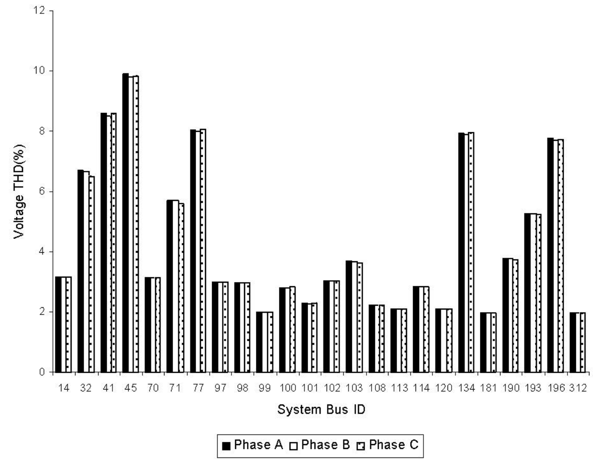

Fig. 4 Voltage THD (%) for 24-bus system when Six Pulse Converter connected at bus ID 32, 41 and 45 with 50% of total load (balanced)

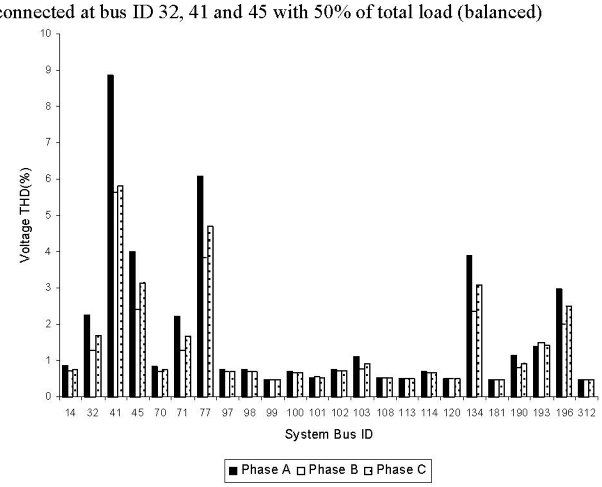

Fig. 5 Voltage THD (%) for TPC 24 bus system when Six Pulse Converter connected at bus ID 41 with 50% of total load (unbalanced).

In the second case, the harmonic voltage is due to unbalanced loading demand; the nonlinear device connected bus's loading demands are adjusted by increasing 20% for phase A, increasing 10% for phase B and decreasing 5% for phase C. For example, the loading demand at bus ID 41 for the 24-bus test system are adjusted by increasing 20% for phase A, increasing 10% for phase B and decreasing 5% for phase C respectively. The adjustment of the loading demand is done according to reference [12] so that the harmonic voltage distortion in the network's buses due to unbalanced loading demand can be obtained and examined.

Fig. 5 shows that when the loading demands for the three-phases are not balanced, the total harmonic distortion for voltage in the connected nonlinear device bus is increased. Similar results were reported in [12]; in which the total harmonic distortion for voltage in the network's buses is compared between balanced with unbalanced loading demands at the connected nonlinear device bus.

VII. Conclusion

The paper has presented an extension of three-phase power-flow object components for unbalanced harmonic analysis. The harmonic penetration algorithm is used and the nodal voltage method for harmonics is developed as an object component. This harmonic analysis required an extension of the basic power system device library to model nonlinear devices. The nodal voltage method component was integrated with the existing three-phase power-flow components in a new component-based application. The high component reuse shows that the complicated power system analysis can be developed with great flexibility which cannot be found in the alternative programming approaches. The proposed component modeling for algorithms can be extended to model more comprehensive methods such as the iterative harmonic solution.

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