A Novel Fast Hybrid Frequency Domain Approach for Evaluating Harmonic Power Flow in Electricity Networks

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Abstract. Ideally, an AC power supply should constantly provide a perfectly sinusoidal voltage signal at every customer location. Nowadays, many power electronic equipment’s are used in industry in seeking higher system reliability and efficiency and more electronic or microprocessor controllers are used in power system to control AC/DC transmission lines or loads. Moreover, the importance of green energy such as wind and solar is continually growing in our societies not only due to environmental concerns but also to resolve the problem of access to electricity in rural areas. As a result of these issues, power quality problems especially generation of harmonics are on the rise in the distribution network. In electrical power system, harmonics have a number of undesirable effects on power system devices as well as on their operation. It therefore becomes imperative for power system engineers to analyse the penetration of harmonics from the various sources into the network which commonly is known as harmonic power flow evaluation. This paper proposed a novel fast hybrid frequency domain approach (FHA) to evaluate the steady state harmonic power flow with discrete harmonic frequency. The proposed method is applied to IEEE – 14 bus, IEEE New England 39 - bus, IEEE – 57 bus and IEEE 118 - bus power system respectively and compared with Newton – Raphson (NR) load flow method and Fast decoupled load flow method (FDLF) and the results validate the accuracy, robustness and authenticity of the proposed method.

Index Terms — Harmonics, IEEE test system, Load flow, Newton – Downhill method, Secant method.

I. INTRODUCTION:

The AC electrical power systems should be designed not only for the sinusoidal voltages and currents but are expected to operate successfully for electronically switched and non - linear loads. Nowadays, the wide implementation of non – linear loads and power electronics devices in real power system such as switched mode power supplies, diode rectifiers, adjustable speed drives, compact fluorescent lamps, HVDC networks, thyristor – controlled reactors, static var compensators, electronic ballasts etc. introduces the considerable number of harmonic currents into the system [1]. Utility companies are particularly concerned with harmonics as one of the major power quality problem since the presence of harmonics causes the deterioration of the power systems voltage and current waveforms,

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thus affecting the operation of electrical equipment’s and also polluting the electric distribution network [2].

The main effects of harmonic distortion of the voltage supply range from possible protective devices ‘nuisance tripping to interference with telephone communication circuits to increased equipment losses that significantly reduces the lifespan of equipment like transformers and cables and to failure of power factor correction capacitors [3]. From the power quality viewpoint, the restructured power market increases the penetration of FACTS controllers and inverter – based power generation units in the transmission activity. In addition, the increasing use of power switching devices at the consumer end worsens poor power quality scenarios [4]. Resonance identification, power system planning, equipment design, among other applications. Further, the related economic impacts of harmonics and electricity market liberalization have all established a need for evaluating harmonic power flow in electricity networks. Over the last decade, many approaches have been proposed and implemented by the researchers for evaluating the harmonic power flow [5].

The term —hybrid represents that the proposed method incorporates three methods: the secant method, the Newton-Downhill method and the decoupled method. The proposed method is successfully tested on IEEE – 14 bus, IEEE New England 39 - bus, IEEE – 57 bus and IEEE 118 - bus power system respectively. The results of computing time, the number of iterations, fundamental and higher harmonic bus voltage magnitudes and the total harmonic voltage distortion are calculated and compared with Newton-Raphson method and the Fast decoupled load flow (DLF) method. The proposed algorithm reduces the number of iterations and solve the convergence problem successfully for all the test cases, thus validating its accuracy, robustness and authenticity as compared to the other load flow methods.

2. Mathematical Modelling of fast hybrid approach (FHA) for Harmonic power flow evaluation.

The performance of the proposed fast hybrid frequency domain method is illustrated in the block diagram shown in Fig. 1.

![Fig.1. The Performance Block Diagram of the Proposed Method (FHA)](image)

As shown in figure 1, the inputs (two guess values) enter the secant method first in order to establish the initial values for the calculation at fundamental frequency. The proposed method combines the Newton-Downhill and the Decoupled method together to calculate the power flow at fundamental frequency thus reduces the calculation process and converge successfully. The initial values at higher harmonic frequencies are included in the calculation. An admittance-matrix based equation is used to calculate the harmonic penetration directly.
A. Secant Method

The secant method is a common and popular variation of the Newton-Raphson method for finding the roots of nonlinear equations. Compared to Newton-Raphson method that approximates the root with a tangent line, the Secant method uses secant lines (hence the need for two initial starting values) to calculate the root of a function \( f \).

\[
y = f(x^k) + \frac{f(x^k) - f(x^{k-1})}{x^k - x^{k-1}}(x - x^k)
\]

Let \( y = 0 \), then the horizontal ordinate at the intersection, \( x_{k+1} \), is:

\[
x^{k+1} = x^k - \frac{x^k - x^{k-1}}{f(x^k) - f(x^{k-1})}f(x^k)
\]

\( k = 1, 2, ... \)

![Fig. 2. The geometrical presentation of the secant](image)

B. Newton – Downhill Algorithm

Newton-Downhill algorithm, a method incorporating Downhill and Newton-Raphson approach, is an optimization algorithm that improves the convergence rate extending its convergence region and does not require initial iteration value calculation. Further, the Downhill algorithm requires less computing time and is more robust as compared to Newton – Raphson method [10, 11].

\[
x^{-(k+1)} = x^k - \frac{f(x^k)}{f'(x^k)} \quad (3)
\]

\[
x^{k+1} = \lambda x^{-(k+1)} + (1 - \lambda)x^k
\]

\[
= x^k - \lambda \frac{f(x^k)}{f'(x^k)} \quad (4)
\]
Where $\lambda$ is the downhill factor, and $0 < \lambda \leq 1$. Thus, the equation (4) is defined as the mathematical expression of the Newton–Downhill algorithm. The downhill factor $\lambda$, plays an important role in the Newton-Downhill algorithm as it expands the convergence scale and decreases the iterations. Hence, it is important to consider its value during the calculation. Normally, let $\lambda = 1$ in the first iteration, then the iterative approximate value $k + 1 \times x$ is achieved in accordance with equation (4).

### C. Novel Fast Hybrid Harmonic Power Flow Evaluation Approach

The fast hybrid harmonic power flow calculation approach (FHA) is an improved iterative approach to calculate harmonic power flow in a power system. It uses the admittance-matrix-based equation to calculate the harmonic power flow directly at higher frequencies ($h > 1$), which is similar to the decoupled method. However, it makes improvements in the harmonic power flow evaluation at the fundamental frequency. It introduces the secant method to establish the iterative initial value in order to tackle the convergence problem caused by the poor initial value.

Two six-pulse line commutated converters are considered as harmonic sources in the present study. The six-pulse converter is basically a poly phase converter and is widely used in household products. It generates more harmonic injection currents than the twelve and twenty-four pulse converters [12]. Hence, the harmonic penetration could be significant. These two six-pulse converters are represented as six-pulse converter-1 and six-pulse converter - 2 respectively.

![Fig 3: Current Balance at a Linear Bus](image-url)
3. Methodology

- The term —hybrid represents that the proposed method incorporates three methods:
- The secant method, the Newton-Downhill method and the decoupled method.
- Proposed method combines the Newton-Downhill and the Decoupled method together to calculate the power flow at fundamental frequency thus reduces the calculation process and converge successfully.

4. Implementation of the Proposed Algorithm and Simulation Results

The location of two six – pulse line – commutated converters as harmonic sources for the different IEEE test cases considered in the present work is shown in the Table 1. The single line diagram of all the IEEE test systems considered in the present work is shown in Appendix I. A MATLAB programming code is written for the proposed algorithm, and thereafter applied to different power systems (i.e. IEEE bus cases).

Table 1. Location of harmonic sources for different IEEE test cases

| S.no | Test Case                  | Location of Harmonic Sources |
|------|----------------------------|-----------------------------|
| 1    | IEEE-14 Bus Power System  | Bus-5 & Bus-9               |
| 2    | IEEE New England 39-Bus Power System | Bus-23 & Bus-29 |
| 3    | IEEE-57 Bus Power System  | Bus-15 & Bus-29             |
| 4    | IEEE-118 Bus Power System | Bus-22 & Bus-95             |
FLOWCHART OF A PROPOSED FHA ALGORITHM:

Choose two initial guesses $x_0$ and $x_i$ in $[0.5,1.5]$ for each bus, and making $f(x_0)f(x_i) < 0$ using equation (7)

Using equation (2) to establish the initial value $\bar{v}^{(1)}$ for each bus (except slack bus)

Iteration = 0

Calculate fundamental power mismatch vector $\Delta \bar{v}^{(1)}$

If $\Delta \bar{v}^{(1)} > \Delta \bar{v}^{(i)}$

Calculate Correction vector $[\Delta^{(1)}, \Delta|\bar{v}^{(1)}|^T]$ using equation 8, and update $\bar{v}^{(1)}$

Update fundamental power mismatch vector $\Delta \bar{w}^{(1)}$

Calculate harmonic admittance matrix $\bar{y}^{(h)}_{bus}$

Output $\bar{v}^{(1)}$

Calculate harmonic bus voltages for each bus $\bar{v}^{(h)}$

Output $\bar{v}^{(h)}$

Fig. 5. Flowchart of a proposed FHA Algorithm
Simulation Results:

Enter the bus system: 14 / 39 / 57 / 118 here: 14
Executing using FAST HYBRID Method
Response of 14.00000 bus system is shown in graph
Number of iterations taken = 3,
Execution time for FHM is : 0.07091 seconds
Executing using Newton Raphson Method
Execution time for NRM is : 0.07289 seconds
Number of iterations taken = 13
Executing using Fast Decoupled Method
Execution time for FDM is : 0.07268 seconds
Number of iterations taken = 7
error values obtained are:

V_fund  THD_vol  P_totals  Ptotalr  Qtotals  Qtotalr  Ptotallossare :
0.00000359  0.00114226  -0.00007327  -0.00006457  -0.00009348  0.00010577  -0.00000866

Run the program again? yes / no : yes

Enter the bus system : 14 / 39 / 57 / 118 here : 39
Executing using FAST HYBRID Method
Response of 39.000000 bus system is shown in graph
Number of iterations taken = 4,
Execution time for FHM is : 0.04766 seconds

Executing using Newton Raphson Method
Execution time for NRM is : 0.05052 seconds
Number of iterations taken = 12

Executing using Fast Decoupled Method
Execution time for FDM is : 0.04968 seconds
Number of iterations taken = 7

error values obtained are
V_fund THD_vol P_totals Ptotalr Qtotals Qtotalr Ptotalloss are:
0.00000099 0.00000815 -0.00003229 -0.00003306 -0.00005623 -0.00005694 0.0000029

Run the program again ?yes / no : yes
Enter the bus system : 14 / 39 / 57 / 118 here : 57

Executing using FAST HYBRID Method
Response of 57.000000 bus system is shown in graph
Number of iterations taken = 3,
Execution time for FHM is : 0.06438 seconds

Executing using Newton Raphson Method
Execution time for NRM is : 0.06773 seconds
Number of iterations taken = 12

Executing using Fast Decoupled Method
Execution time for FDM is : 0.06613 seconds
Number of iterations taken = 8
error values obtained are
V_fund THD_vol P_totals Ptotalr Qtotals Qtotalr Ptotalloss are:
0.00000715 0.00434226 -0.00001799 -0.00001801 0.00007667 0.00000276
Run the program again ?yes / no : yes
Enter the bus system : 14 / 39 / 57 / 118 here : 118
Executing using FAST HYBRID Method

Response of 118.000000 bus system is shown in graph
Number of iterations taken = 4,
Execution time for FHM is : 0.18905 seconds

Executing using Newton Raphson Method
Execution time for NRM is : 0.20257 seconds
Number of iterations taken = 13

Executing using Fast Decoupled Method
Execution time for FDM is : 0.19723 seconds
Number of iterations taken = 7

error values obtained are

V_fund THD_vol P_totals Ptotalr Qtotals Qtotalr Ptotalloss are :

0.00001587 0.00301132 -0.00008055 -0.00007177 0.00010173 0.00009656 0.00000339
Table 2. Comparison of Results obtained for all IEEE test cases

| Comparison Parameter | Methods | IEEE – 14 Bus System | IEEE – 39 Bus System | IEEE – 57 Bus System | IEEE – 118 Bus System |
|----------------------|---------|----------------------|----------------------|----------------------|----------------------|
| No. of Iterations    | FHM     | 3                    | 4                    | 3                    | 4                    |
|                      | NRM     | 13                   | 12                   | 12                   | 13                   |
|                      | FDM     | 7                    | 7                    | 8                    | 7                    |
| Execution Time       | FHM     | 0.04766 Sec          | 0.06438 Sec          | 0.07091 Sec          | 0.18905 Sec          |
|                      | NRM     | 0.05052 Sec          | 0.06773 Sec          | 0.07289 Sec          | 0.20257 Sec          |
|                      | FDM     | 0.04968 Sec          | 0.06613 Sec          | 0.07268 Sec          | 0.19723 Sec          |

** NR Method and FDLF method fail to converge at when the initial bus voltage magnitude is 0.6 p.u and 0.5 p.u for all the four IEEE test systems.

Table 3. Error values obtained for all IEEE test cases

| Parameter (error Values) | IEEE – 14 Bus System | IEEE – 39 Bus System | IEEE – 57 Bus System | IEEE – 118 Bus System |
|--------------------------|----------------------|----------------------|----------------------|----------------------|
| $V_{\text{fund}}$       | 0.000000359          | 0.00000099          | 0.00000099          | 0.00001587          |
| THD_Vol                  | 0.00114226          | 0.00000815          | 0.00000815          | 0.00301132          |
| P_totals                 | -0.00007327         | -0.00003229         | -0.00003229         | -0.00008055         |
| P totalr                | -0.00006457         | -0.00003306         | -0.00003306         | -0.00007177         |
| Q totals                 | -0.00009348         | -0.00005623         | -0.00005623         | 0.00010173          |
| Q totalr                | 0.00010577          | -0.00005694         | -0.00005694         | 0.00009656          |
| P totalloss              | -0.00000866         | 0.00000029          | 0.00000029          | 0.00000339          |

5. Analysis

- The fast hybrid harmonic power flow calculation approach (FHA) is an improved iterative approach to calculate harmonic power flow in a power system.
- It uses the admittance-matrix-based equation to calculate the harmonic power flow directly at higher frequencies ($h > 1$), which is similar to the decoupled method.
- It introduces the secant method to establish the iterative initial value in order to tackle the convergence problem caused by the poor initial value.
• A MATLAB programming code is written for the proposed algorithm, and thereafter applied to different power systems (i.e. IEEE bus cases).

6. Results and Discussion

• The proposed method is successfully tested on IEEE – 14 bus, IEEE New England 39 - bus, IEEE – 57 bus and IEEE 118 - bus power system respectively.
• The results of computing time, the number of iterations, fundamental and higher harmonic bus voltage magnitudes and the total harmonic voltage distortion are calculated.
• The results are compared with Newton – Raphson (NR) load flow method and Fast decoupled load flow method (FDLF) and the results validate the accuracy, robustness and authenticity of the proposed method.
• The proposed algorithm reduces the number of iterations and solve the convergence problem successfully for all the test cases, thus validating its accuracy, robustness and authenticity as compared to the other load flow methods.

7. Conclusion

In this paper, a novel fast hybrid method (FHM) that combines the secant method, the Newton-Downhill method and the decoupled method has been proposed and presented. The validation of the algorithm and comparative simulation results in four different IEEE test systems has been illustrated. Compared with NR method and FDLF method, the proposed method has less iteration numbers and computation time and provide high accuracy and better performance. Also, the NR method and FDLF method fail to converge when the initial bus voltage magnitude is 0.6 p.u. and 0.5 p.u. for all the four IEEE test systems considered in the present work. Moreover, the proposed FHM method is reliable in terms of convergence (i.e. converged successfully) as it used the secant method to establish the iterative initial value. In conclusion, the proposed FHM method can accomplish the harmonic power flow calculation both for small and large power systems effectively and with an acceptable level of accuracy.

8. Future Scope

• Real-time loading and different Harmonic power flow studies can be used to further assess FHA efficacy under unfavourable conditions.

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