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Coordinated active and reactive power management of microgrids in ride-through modes base on improved droop controls

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Abstract

This paper presents a coordinated active and reactive power management of Microgrid with hierarchical control scheme. Microgrid is divided into clusters as the load requirement of power quality and reliability, i.e., multi-cluster architecture. Each cluster is managed individually by a cluster controller in coordination with local controllers of DG units. A hierarchical control scheme is employed with three levels including droop controls, load frequency controls and reserves. An improved droop control is introduced considering the comparability of resistance and inductance of the low-voltage network, the inter-relation of voltage and active power, as well as frequency and reactive power are taken into accounts. The proposed control scheme is applied to a case study in which a two-cluster Microgrid with three DG units is experiencing the ride-through mode after disconnecting from the main grid. The result of simulation shows the effectiveness of the proposed method.

Keywords: Microgrid, distributed generation, hierarchical control scheme, improved droop control

1. Introduction

Microgrid is a small, medium- or low-voltage power system which employs distributed generation (DG) and energy storage (ES) to supply the local loads or communities. Microgrid can be built either in forms of AC, DC, hybrid or multiple electric networks based on the feature of the power generation and consumption [1-2]. Different prime-mover technologies such as photovoltaic (PV), fuel cell (FC), microturbine (MT), etc. are adapted through power electronic interfaces, allowing Micorgrid to operate in various modes: grid-connected, islanded, and seamlessly transit between them. Generally, the control of Microgrid is designed with the legacy of droop and load frequency controls, etc. but can be performed either in centralized or decentralized paradigm [3].

In centralized, the economic operation of Microgrid is computed according to the forecasting data such as loads, weathers, electricity prices and the availability of the main grid [4-6]. The droop, load frequency control and reserves are manipulated by the central controller to maintain the power balance of Microgrid in different time bases [7,8]. In decentralized, the autonomous active and reactive power control of inverter-based DG was introduced in [9,10]. It is achieved by modifying the traditional droop control considering the dominance of resistances over inductances in local networks, making DG better responding to the load variation, reducing the voltage and frequency deviation of Microgrid. An improved cost-based droop control is proposed with the droop offset weighted by the cost reference [11]. The objective is providing an optimal load-sharing between DG units at a least-cost of generation. The fuel cost of DG is further analyzed for a better weighted factor, which is more accurate in representing the actual generation cost of DG at various cases: loaded [12] and no-load condition [13]. Another droop

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control for improving reactive power sharing in islanded Microgrid is proposed in [14] considering the mismatched impedance of DG and loads. It is done by introducing an adaptive virtual impedance to modify the voltage reference based on measures of the output current; as results, the error of reactive power sharing can be reduced.

Although many efforts have been paid to develop the control of Microgrid, the characterization of different control paradigms is still not well defined. The hierarchical control can be used as centralized in some researches but decentralized in others. In addition, the droop control is mainly based on the assumption of dominances of either inductivity or resistivity in power networks, which is not always correct. Instead, the resistance and inductance are more or less comparable in medium- or low-voltage systems. In this paper, we proposed the multi-cluster architecture of Microgrid in which the system is divided and monitored using a hierarchical control scheme. The control of each cluster is designed according to the requirement of loads; thus the cluster can operate in islanded mode if fault occurs or not. Then, an improved droop control scheme for coordinated active and reactive power control is proposed. It is taken into account the co-relationship of the system variables, thus, DG units should adjust active and/or reactive power according to the change of both voltage and frequency. As results, the deviation and frequency in response to the variation of loads can be reduced.

The remainder of this paper is organized as follows. Section 2 presents the structure of multi-cluster Microgrid and hierarchical control scheme. Section 3 develops the improved droop control from the traditional scheme. Section 4 shows a case study of two-cluster Microgrid where the proposed scheme is applied. Finally, the remarkable points and importance of the paper are summarized in Conclusion.

2. Multi-Cluster Microgrid

2.1. Multi-cluster structure

There are a number of topologies of Micogrid that have been studied and reported in literature. Clustering Micogrid into autonomous agents, zones or branches with the aim to improve the integrity, controllability, flexibility and reliability of DG and loads was reviewed in [15]. In this paper, we introduce multi-cluster Microgrid as expressed in Fig. 1.

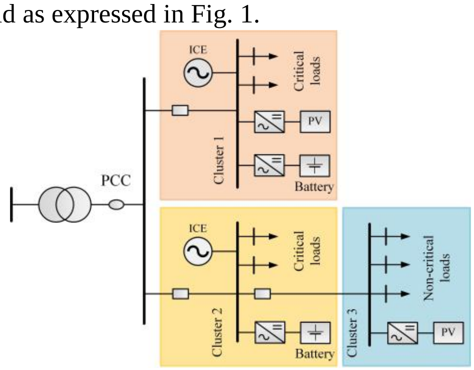

Fig. 1. Multi-cluster Microgrid architecture.

It can be seen that Microgrid is divided into three clusters. The reason is satisfying the load requirement. Some loads that draw a small amount of power but require a very high reliability, interruptions even in milliseconds can cause dramatic monetary losses, e.g., in data centers, banking systems, etc. In contrast, some other loads consume a large power, but interruption in few seconds or even minutes may not be realized, such as water boiler, heating/cooling systems, etc. Therefore, it would be more economical if loads are fed the with different reliability as desired. In the proposed Microgrid, important loads (critical) are arranged in clusters with sufficient installed DG and ES units. When a fault occurs in the main grid, this cluster will be isolated and controlled autonomously, maintaining the continuity of power supply. Other loads (noncritical) are in clusters which will be curtailed intentionally in emergency. Designs of critical/noncritical clusters will be done through the market transaction. The users themselves will decide their load to be critical or not as their willingness to pay: The higher the reliability, the more money to pay.

2.2. Hierarchical control scheme

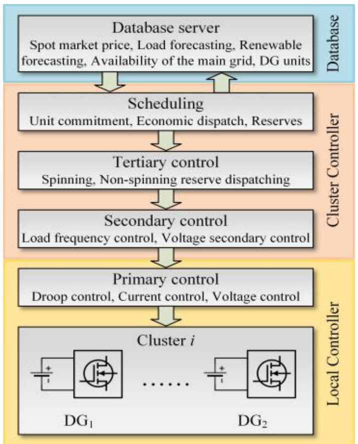

Fig. 2. The hierarchical control scheme.

In multi-cluster Microgrid, each cluster is designed with hierarchical controls and monitored individually by cluster controller (CC) and local controller (LC) as in Fig. 2. The role of CC is performing two main functions: (1) optimal scheduling and (2) real-time control of the cluster in both grid-connected and islanded modes, and also seamless transition between them. In scheduling, CC would have free access in the database for information such as load forecasting, spot market price and the availability of DG units and the main grid, etc. to compute the day-ahead schedule which maximizes the expected profit in the spot market. The schedule would indicate the set-point of DG and charging/discharging of ES units in each stage of the next day. Probably, it includes the decision of load curtailments if demand response (DR) is applied. Scheduling of reserves is also considered particularly in case of losing the connection to the main grid. The cluster will experience a “ride-through” period, guaranteeing the supply of important loads before a new optimal allocation of the resource is determined. In operation, a real-time economic dispatch will be used to improve the optimality of Microgrid. It is to revise the pre-determined schedule in response to the variation of loads and the market price in a shorter time-basis, making DG units operating with the marginal cost (MC) closer to the real-time price (which is updated in the database). The set-points are then sent to LC installed in individual DG and ES unit.

3. Improved Droop Controls

In grid-connected, the voltage and frequency of Microgrid can be monitored easily with supports from the main grid; the PCC will act as an infinite bus, maintaining the active and reactive power balances. In contrast, the issue is much more complicated in islanded modes where the cluster needs to handle the load itself. It is not only depending on the amount of reserves but also the characteristic of DG units and loads. Therefore, the traditional hierarchical control needs to be revised appropriately and effectively to apply in the islanded mode.

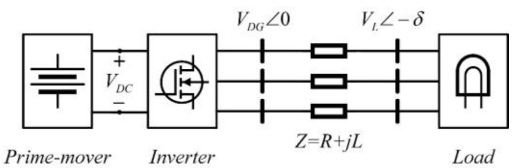

Fig. 3. A simple case of Microgrid.

Consider a simple Microgrid with a DG unit supplying load through power lines. The active power and reactive power can be expressed as follows [16].

$$
\begin{aligned}
P_{DG} &= \frac{V_{DG}^2}{Z}\cos\theta - \frac{V_{DG}V_L}{Z}\cos(\theta+\delta) \\
Q_{DG} &= \frac{V_{DG}^2}{Z}\sin\theta - \frac{V_{DG}V_L}{Z}\sin(\theta+\delta)
\end{aligned}
\quad (1)
$$

Where P_{DG} and Q_{DG} are the active and reactive power of DG, $\dot{Z} = Z\angle\theta = R + jX$ are the impedance with R is the resistance and X is the reactance of the power line, V_{DG} and V_L are the voltage amplitude at DG and load center, δ is the power angle, i.e., the phase difference of the voltage at DG and load.

The conventional droop control is based on the assumption that the inductance is dominant the resistance of the network $(X >> R)$ and the power angle is small. The power injected by DG can be approximated as follows.

$$
\begin{aligned}
P_{DG} &= \frac{V_{DG}V_L}{X}\delta \\
Q_{DG} &= \frac{V_{DG}^2}{X} - \frac{V_{DG}V_L}{X}
\end{aligned}
\quad (2)
$$

In this case, the frequency (power angle) is closely relative to the active power while the voltage is associated with the reactive power, independently. This results in the well-known Q-V and P-f droop controls expressed in Fig. 4 and Eq. (3).

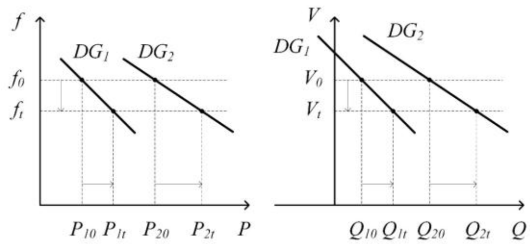

Fig. 4. The conventional P-f and Q-V droop controls.

$$
\begin{aligned}
f - f_0 &= -k_P\left(P_{DG} - P_{DG0}\right) \\
V_{DG} - V_{DG0} &= -k_Q\left(Q_{DG} - Q_{DG0}\right)
\end{aligned}
\quad (3)
$$

Where f_0 and V_0 are the set value of frequency and voltage in Microgrid; k_P and k_Q are the droop coefficients of DG (which is set according to the inverter's ratings); P_{DG0}, Q_{DG0}, P_{DG} and Q_{DG} are the scheduled and actual active and reactive power of DG. If there is a change of loads, DG will respond to adjust the active and reactive power instantaneously, balancing the amount of generation and consumption at a slightly deviation of frequency and voltage.

However, Microgrid normally employs medium or low voltage systems which has predominant resistivity $(R >> X)$, the power injected by DG will be expressed as follows [17].

$$
\begin{aligned}
P_{DG} &= \frac{V_{DG}^2}{R} - \frac{V_{DG}V_L}{R} \\
Q_{DG} &= -\frac{V_{DG}V_L}{R}\delta
\end{aligned}
\quad (4)
$$

In Eq. (4), it can be seen that the active power is mainly linked with the voltage while the reactive power is related to the power angle. Therefore, P-V and Q-f droop control are introduced [17].

$$
\begin{aligned}
V_{DG} - V_{DG0} &= -k_P\left(P_{DG} - P_{DG0}\right) \\
f - f_0 &= k_Q\left(Q_{DG} - Q_{DG0}\right)
\end{aligned}
\tag{5}
$$

In general cases, X and R are comparable and both need to be considered [18]. It is proposed modified active and reactive power (P' and Q') are as follows.

$$
\begin{aligned}
P' &= \frac{X}{Z}P_{DG} - \frac{R}{Z}Q_{DG} \\
Q' &= \frac{R}{Z}P_{DG} + \frac{X}{Z}Q_{DG}
\end{aligned}
\tag{6}
$$

Substitute Eq. (1) into (6) with the assumption of the small power angle, we can obtain:

$$
\begin{aligned}
P' &= \frac{V_{DG}V_L}{Z}\delta \\
Q' &= \frac{V_{DG}^2}{Z} - \frac{V_{DG}V_L}{Z}
\end{aligned}
\tag{7}
$$

Eq. (7) shows the dependency of the modified active power on the power angle as well as the modified reactive power on the voltage. Thus, droop control in Eq. (3) can be applied as follows.

$$
\begin{aligned}
f - f_0 &= -k_P\left(P' - P_0'\right) \\
V_{DG} - V_{DG0} &= -k_Q\left(Q' - Q_0'\right)
\end{aligned}
\tag{8}
$$

Substitute Eq. (6) into (8), we can obtain droop control in general cases [Fig. 5]:

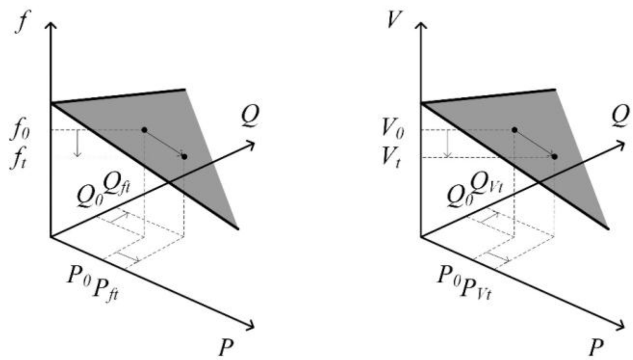

Fig. 5. The improved P-fV and Q-fV droop controller.

$$
\begin{aligned}
f - f_0 &= -K_{P1}\left(P_{DG} - P_{DG0}\right) + K_{Q1}\left(Q_{DG} - Q_{DG0}\right) \\
V_{DG} - V_{DG0} &= -K_{P2}\left(P_{DG} - P_{DG0}\right) - K_{Q2}\left(Q_{DG} - Q_{DG0}\right)
\end{aligned}
\tag{9}
$$

Where $K_{P1} = k_P X/Z$, $K_{P2} = k_P R/Z$, $K_{Q1} = k_Q R/Z$, $K_{Q2} = k_Q X/Z$ are the modified coefficient of the droop control in the general case.

In the hierarchical scheme, droop controls serve as the primary regulation which aims to balance Microgrid in few seconds with a small, acceptable deviation of frequency and/or voltages. To recover

Microgrid to its nominal value, the secondary regulation is employed to compensate the normal (slow and small) variation of loads (and renewable DG, if existed). It is called load frequency control or load following control. It is done by allocating the power mismatch amongst DG and ES units (partially provided by the primary control and load responsiveness). The criteria of sharing can be the capacity, the amount of reserve and/or cost reference.

$$\begin{aligned} \Delta P_{DGi} &= K_{DGi} \cdot \left(K_{Pf} \Delta f + \sum_{i=1}^{N} K_{PVi} \Delta V_{DGi} \right) \\ \Delta Q_{DGi} &= K_{DGi} \cdot \left(K_{Qf} \Delta f + \sum_{i=1}^{N} K_{QVi} \Delta V_{DGi} \right) \end{aligned} \tag{10}$$

Where K_{Pf}, K_{PV}, K_{Qf}, and K_{QV} is the responsiveness of the DG and load at each bus to the change of the frequency and voltages, K_{DG} is the participation factor of DG in the secondary regulation, Δf and ΔV are the deviation of frequency and voltages, and N is the number of bus.

4. Case Study

In this section, the proposed scheme is tested in an illustrative MG model [Fig. 6]. The system is divided into two clusters: Cluster 1 is with noncritical loads while cluster 2 is with critical. It is assumed that in the beginning, Microgrid is operating in connections with the main grid. At the time t = 0.5 seconds, a fault occurs, the protection device responds to open the static switch (SS). Cluster 1 with DG_1 will be interrupted while cluster 2 is transiting to islanded mode and operating autonomously with DG_2 and DG_3 supplying the local load. The CC of cluster is activated to control DG_2 and DG_3 in the ride-through mode, the imbalance power will be shared equally between the available sources before a new optimal dispatching is determined. The simulation is created in Matlab 2016a – Simulink toolbox. The result of simulation is expressed as follows.

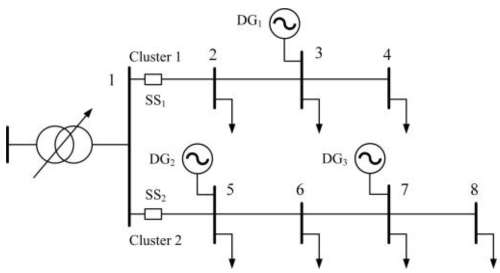

Fig. 6. The two-cluster Microgrid in the case study.

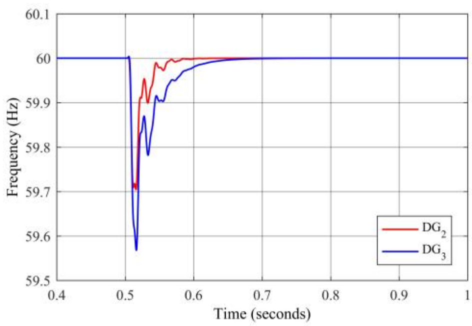

Fig. 7. The frequency of DG_2 and DG_3 in the ride-through mode.

The frequency and voltage response of DG_2 and DG_3 is displayed in Fig. 7 and 8. Initially, the Micorgid is synchronous with the main grid and the frequency is remained constant (60 Hz); the voltage is assumed at nominal value (1.0 pu). When the connection is lost, the imbalance power makes the frequency and voltage to decay. At primary level, the droop control will respond first to provide more active and reactive power, lifting the frequency and voltage to a smaller deviation. Then, at secondary level, the load frequency control will act to recover the frequency and voltage to its minimal value. The response of DG_2 and DG_3 depends on their response times which are slightly different based on the prime-mover technology and excitation system or the controller of power electronic interfaces.

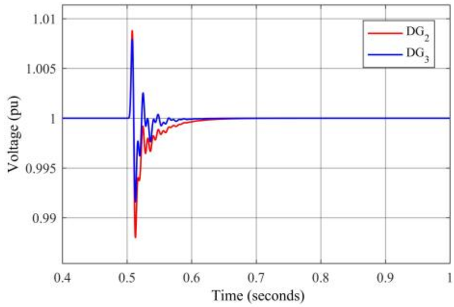

Fig. 8. The voltage of DG_2 and DG_3 in the ride-through mode.

It can be seen that in the beginning of ride-through mode, the droop control makes an over shoot of the voltage. It is because the voltage is controlled with electrical signals through excitation system or power electronic devices which is much faster than the frequency response, making the reactive power is over compensated in the beginning; that will be revised later by the secondary voltage control.

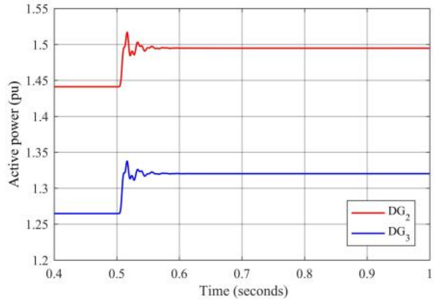

Fig. 9. The active power of DG_2 and DG_3 in the ride-through mode.

The active and reactive power provided by DG_2 and DG_3 are displayed in Fig. 10 and 11. The imbalance power are assumed to shared equally between two DG units in ride-through mode. The ride-through mode starts when Microgrid is disconnected from the main grid. It lasts until a new optimal operation is computed by CC (based on the load and available DG sources of the cluster) and sent to LC to implement.

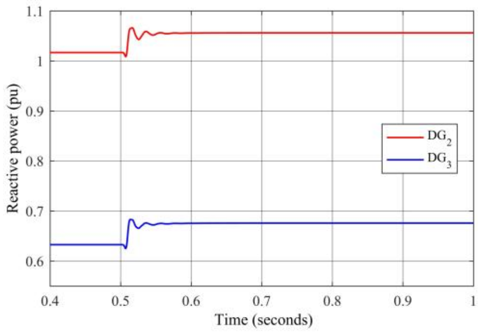

Fig. 10. The reactive power of DG_2 and DG_3 in the ride-through mode.

The phase voltage and current measured at the terminal of DG_2 and DG_3 are displayed in Fig. 11-14. It can be seen that the currents in different phases are changing significantly different; it is due to the actual value of the current at the instance of time when the hierarchical control is activated. Also, the value of current increases significantly to provide more the active and reactive power for Microgrid.

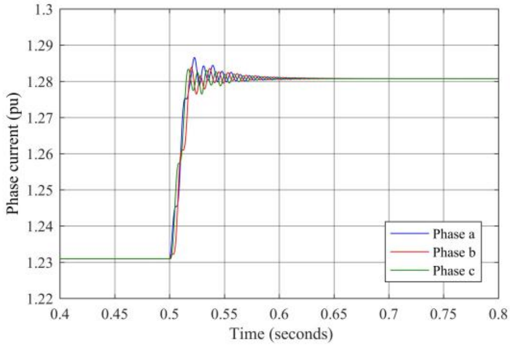

Fig. 11. The phase current of DG_2 in the ride-through mode.

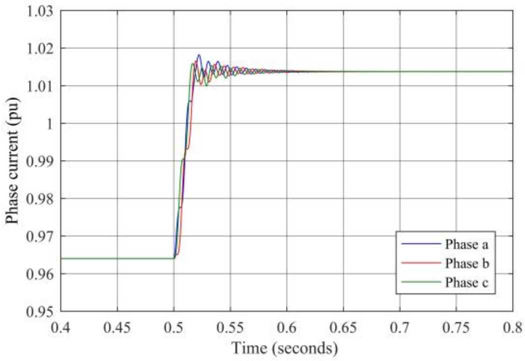

Fig. 12. The phase current of DG_3 in the ride-through mode.

For the phase voltage, it is noted that although the droop and load frequency control aim to increase the voltage, the terminal voltages are slightly decrease. It is because the output current is increased, making the voltage drop due to the internal impedance increased as well. As results, the terminal voltage is decreased but within acceptable ranges (+5% and –10%).

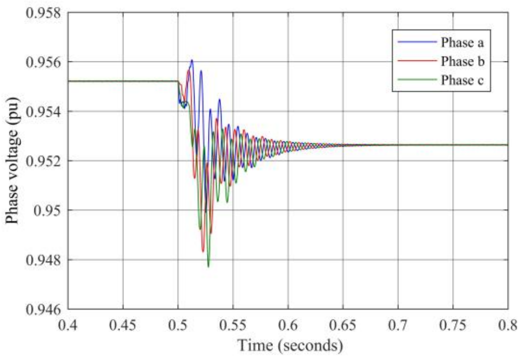

Fig. 13. The phase voltage of DG_2 in the ride-through mode.

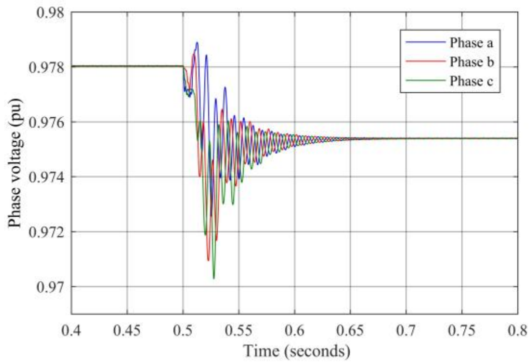

Fig. 14. The phase voltage of DG_3 in the ride-through mode.

5. Conclusion

In this paper, a coordinated active and reactive power management of Microgrid with hierarchical control scheme was proposed. At primary level, an improved droop control was developed taking into account the inter-relation of voltage and active power, as well as frequency and reactive power. It is due to the fact that Microgrid normally employed medium- or low-voltage systems in which the resistivity and inductivity are comparable; thus, the inter-dependence of frequency, voltage and active and reactive power cannot be ignored. In addition, with the proposed multi-cluster architecture, the electric users are capable of choosing the quality and reliability of power supply as desired. This is done through the market environments with different electric tariffs: the higher the price, the better the service provided.

In case study, the proposed control scheme was applied to a two-cluster Microgrid with three DG units in ride-through mode. Simulation result showed that when the connection to the main grid is lost, the critical cluster can promptly respond to supply its load, guaranteeing Microgrid to survive through emergency. Then, CC is switched to autonomous mode, the optimal operation (set-points) is computed according to the current load and the availibity of DG units. The set-point will be sent to LC to take in controls. The ride-through mode will be terminated.

It is expected that many advantages can be realized from the multi-cluster structure and the improved droop control of Microgrid. In future work, we will try to analyze this proposal and apply in other functions of Micogrid such as optimal operation, resynchronization and uncertainty management, etc.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

Nguyen M.Y. conducted the entire research and wrote the paper. The author had approved the final version.

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