Nigerian Journal of Engineering, Vol. 30, No. 1, April 2023, ISSN (print): 0794 – 4756, ISSN(online):2705-3954.

Nigerian Journal of Engineering,
Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria
journal homepage: www.njeabu.com.ng

Load Frequency Control of a HVDC - Linked Multi - Area Interconnected Power System

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Research Article

Abstract

In this paper, a load frequency control (LFC) of high voltage direct current (HVDC)-linked interconnected multi-area power system (MPS) is presented. The control scheme is aimed at maintaining a near-zero steady state errors for deviation in frequency and inter-area power flow within acceptable limit in a three-area MPS. The proposed LFC was realized with aid of proportional integral (PI) controller designed in a decoupled form and a supplementary power modulation controller (SPMC). The SPMC regulates flow of DC power through the DC-link. The PI controllers are optimized based on integral square error (ISE) using quasi-oppositional whale optimization algorithm (QOWOA). The efficacy of the proposed LFC scheme was demonstrated through time-based simulations in MATLAB/Simulink environment. The system responses are compared with those obtained in conventional AC system. The comparative analysis revealed the superiority of the developed QOWOA-optimized HVDC-linked over the conventional AC system. The overshoot and settling times of frequency deviation and tie-line powers are used as the performance metrics.

doi: 10.5455/nje.2023.30.01.07

Keywords
Load frequency control, HVDC, supplementary power modulation controller, whale optimization algorithm.

Article History
Received: – October, 2022
Reviewed: – January, 2023
Accepted: – April, 2023
Published: – April, 2023

1. Introduction

Automatic generation control (AGC) is the most difficult task in the control of large-scale dynamic systems like electrical power system (PS). To reduce the computational complexities and difficulties in the implementation of the AGC, advanced controllers are used in place of classical ones. In addition, for ease of control, implementation of market and energy policies, the PSs are often partitioned into multiple control areas (CAs). These CAs are linked together via transmission lines known as tie-lines, and together form a system called Multi-area Power Systems (MAPS). Each of the subsystem has its own generating units responsible for its own electrical power demand and scheduled power interchanges with adjoining subsystems through tie-lines. In such interconnected systems, frequency deviation does not only occur due to imbalance between generation and demand but also change in power flow between neighboring CAs via the tie-lines. Subsequently, these deviations initiate an accelerating or decelerating effect on the generation facilities (majorly synchronous generators) which can cause devastating effects on the system (Shiroei & Ranjbar, 2014; Sujan, *et al*., 2017). Among the consequences include malfunction of relays and network protection equipment, damage to power plant turbines, the partial loss of load, loss of synchronism, and eventually lead to system collapse (Fathy & Kassem, 2018). Sustaining uninterrupted balance between electrical power generation and spontaneous load demand is the key to the successful operation of power systems. Some generating units known as spinning reserves participate in the AGC of the MAPS. They are used to maintain system frequency and tie-line powers within certain allowable limits through a technique known as LFC (Sujan, *et al*., 2017; Saxena & Hote, 2016). In the words, an AGC system, as a second loop of LFC, is designed for each CA and is responsible for maintaining frequency deviations within the permissible range as well as for power exchanges between the CAs close to the scheduled values following variations in the system load or any disturbances (Ersdal, e*t al*., 2015; Ma, *et al*., 2014).

Earlier frequency control scheme used flyballs to activate a hydraulic system for adjusting the throttle valves of the system prime movers. Modern generators use electronic governors to accomplish the same task (Zhang, *et al*., 2017; Stil & Mehmedovic, 2018).

There are numerous research works carried out on LFC and generally apply optimal, robust, adaptive and intelligent control approaches. Among the approaches proposed are classical control such as PI in (Guolian *et al*., 2011; Simhadri & Mohanty, 2019) and PID controllers (Abd-Elazim, 2010; Mehta, *et al*., 2017; Hota & Mohanty, 2016). For instance, (Fathy & Kassem, 2018) proposes optimal LFC) designed by Adaptive Neuro-Fuzzy Inference System (ANFIS) trained via antlion optimizer (ALO) for multi-interconnected system comprising renewable energy sources (RESs). The input and output of the optimized PI controller are used to train the ANFIS-LFC with gaussian surface membership functions. In addition, (Abd-Elazim, 2010) employed a Bacterial Foraging Optimization Algorithm (BFOA) to determine the optimal parameters of the controller and revealed its improved performance compared to Genetic Algorithm (GA)-tuned PI in a bi-CA non-reheat thermal MAPS. An LFC of a thermal MAPS using PI tuned with Grey Wolf Optimization algorithm based modified the objective function using Integral of Time Multiplied by Absolute Value of Error (ITAE) is proposed in (Saikia, 2015). The results were compared with those obtained using BFOA and GA optimized ITAE-based PI controller to establish its effectiveness and superiority. Similarly, in (Simhadri & Mohanty, 2019), quasi-oppositional whale optimization algorithm (WOA) is employed to tune a dual-mode PI controller serving as supplementary frequency controller. A modified differential evolution algorithm optimized fuzzy PID controller is proposed in (Sahoo, *et al*., 2018). To improve the performance, the fuzzy PID controller is reinforced with thyristor-controlled series compensator. In a similar study, application of fuzzy PI controller for LFC of a linear and nonlinear MAPS is investigated in (Satapathy, et al., 2018). The gain of the controller in tuned using Jaya optimization algorithm with and without consideration of the governor dead band (GDB) effect. In (Pradhan & Bhende, 2019), same optimization algorithm, due to its simplicity and speed is applied to tune a fuzzy controller online for LFC of WT integrated MAPS.

With the increased integration of renewable energy based distributed generators (DGs) and geographical expansion of MAPS, classical control schemes encounter numerous setbacks ranging from optimality, stability, strict constraints handling and uncertainties in the system states. As such, optimal and robust control techniques like model predictive control (MPC) (Zhang, *et al*., 2017; Ma, *et a*l., 2014; Yang, *et al*., 2021), linear quadratic regulator (LQR) (Kumari & Jha, 2014; Rahman, et al., 2018), fractional-order controller via internal model control (Saxena, 2019) are equally applied despite their own downsides. For instance, (Xia & Liu, 2019) proposes a coordinated control strategy for AGC units across areas based on bi-level MPC to achieve resource sharing. The control scheme uses economic MPC to realize steady power optimal allocation of the AGC units across areas and realize dynamic frequency optimization control in a three-area AC/DC interconnected power grid with a wind farm.

In this research, LFC of 3-CA parallel AC/DC interconnected MAPS is proposed. Each of the three CAs will be equipped with a QOWOA optimized PI controllers in a decentralized pattern, to control the frequency and tie-line power. The optimal gains of the controllers will be obtained by considering controller gains limits, frequency limit and GRC limits as constraints. The study will further reveal the advantages of having parallel HVDC links over single AC tie line.

2. Multi-Area System Modelling

In this section, the methods adopted or developed in order to come up with the proposed MAPS, PI and the SPMC controllers, together with the algorithm used in tuning them are discussed.

2.1 Multi-Area System Modelling

Each of the control area in the three-area system is modelled separately by using *swing equation*; linearized differential equation describing the generator's dynamics, illustrated in (1)

$$\frac{df_i}{dt} = \frac{1}{M_i}\left(P_i^G - D_i f_i - P_i^{tie} - P_i^D\right) \qquad (1)$$

Where M_i is the equivalent inertia constant of *i*th control area. With the assumption that generators in that area form coherent group, single frequency (f_i) is defined. Generation from ψ individual generators summed up to give the total area generation, P_i^G as given in (2) (Keerthana & Selvi, 2018),

$$P_i^G = \sum_{j=1}^{\psi} P_{i,j}^G; \quad and \quad P_{D_i} = \sum_{j=1}^{\mu} P_{D_{i,j}} \qquad (2)$$

P_i^D is the total demand of *i*th CA obtained by adding up load demands of all the μ load points as shown in (2).

To model the tie-line power between two adjoining control areas, approximate AC power flow model is used, as expressed in (3),

$$\frac{dP_i^{tie}}{dt} = \sum \dot{P}_{ij}\,; where\ \frac{dP_{ij}}{dt} = 2\pi T_{ij}^0\left(f_i - f_j\right) \quad (3)$$

Where T_{ij}^0 is the synchronizing coefficient expressed as a function of the of *i–j*th line static transmission capacity.

The power output of the turbine is regulated by a careful adjustment of the control valves' position, which control the flow of steam/water to the turbines. For small disturbance, the turbine dynamics of the gth generator in the *i*th CA is modelled as;

$$\frac{dP_i^G}{dt} = \frac{1}{T_T}\left(P_i^{Gov} - P_i^G\right) \qquad (4)$$

Each generator is supplied with a supplementary control signal, P_i^{sc}, however, valve position cannot be adjusted at infinite speed. Hence, further dynamics is introduced into the system as governor model. The change in governor valve position as it relates to frequency is represented as in (5).

$$\frac{dP_i^{Gov}}{dt} = \frac{1}{T_{gov}}\left(P_{i,g}^{cont} - P_i^{Gov} - \frac{1}{R_i} f_i\right) \qquad (5)$$

For implementing LFC in a multi-area system, the concept of Area Control Error (ACE) was introduced. The ACE, formed by combining the deviation in frequency and tie-line power as shown in (6), is utilized in the dynamic controller as a feedback input for optimal computation of $P_{i,g}^{cont}$. Thus, for ith CA,

$$\mathrm{ACE}_i = \beta_i f_i + P_i^{tie} \quad (6)$$

ACE is used as system output as well as performance measure in LFC. The model presented in (1) – (6) is the continuous time (CT) model of LFC in MAPS. This model is represented in state-space as shown in (7) and (8);

$$\frac{d}{dt}\begin{bmatrix} f_i \\ P_{i,g}^G \\ P_i^{gov} \\ P_i^{tie} \end{bmatrix} = \begin{bmatrix} -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 & -\frac{1}{M_i} \\ 0 & -\frac{1}{T_{T_{i,g}}} & \frac{1}{T_{T_{i,g}}} & 0 \\ -\frac{1}{R_{i,g}T_{Gov_{i,g}}} & 0 & -\frac{1}{T_{Gov_{i,g}}} & 0 \\ 2\pi\sum T_{ij}^0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} f_i \\ P_{ii}^G \\ P_i^{Gov} \\ P_i^{tie} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{Gov_{i,g}}} \\ 0 \end{bmatrix} P_{i,g}^{cont} + \begin{bmatrix} -\frac{1}{M_i} \\ 0 \\ 0 \\ 0 \end{bmatrix} P_i^D + \begin{bmatrix} -\frac{1}{M_i} \\ 0 \\ 0 \\ -2\pi\sum T_{ij}^0 \end{bmatrix} f_j \quad (7)$$

$$\mathrm{ACE}_i = (\beta_i \quad 0 \quad 0 \quad 1)\left(f_i \quad P_i^G \quad P_i^{gov} \quad P_i^{tie}\right)^T \quad (8)$$

The state vector, x_i is defined as $\left[f_i \quad P_{i,g}^G \quad P_{i,g}^{Gov} \quad P_i^{tie}\right]^T \in \mathbb{R}^4$ is the state vector, $u_i = P_{i,}^{cont}$ is the supplementary control signal, P_i^D is the system disturbance within the ith control area, while $d_i^{ext} = f_j$ is the disturbance attributed to frequency deviations from neighboring control areas and $\mathrm{ACE}_i: \forall i = 1, 2, \ldots n$ is the system output.

The transfer function model of the HVDC link is considered to be operating in constant current control mode, and the incremental DC power flow through the link is modelled with incremental change in frequency at the rectifier end as,

$$P_{DC_{ij}}^{tie} = \frac{K_{dc}}{1 + sT_{dc}}(\Delta f_i - \Delta f_i) \quad (9)$$

Where K_{dc} denotes HVDC modulation coefficients and T_{dc} represents the time constant. With the introduction of the DC-line, the tie-line power in the MAPS comprises of both DC-line and AC-line powers, $P_{AC_i}^{tie}$ expressed as;

$$P_i^{tie} = P_{DC_i}^{tie} + P_{AC_i}^{tie} \quad (10)$$

Hence, the ACE expressed in (8) is modified to take the effect of the HVDC as

$$\mathrm{ACE}_i = (\beta_i \; 0 \; 0 \; 1)\left(f_i \quad P_{i,g}^G \quad P_{i,g}^{Gov} \quad \left(P_{DC_i}^{tie} + P_{AC_i}^{tie}\right)\right)^T \quad (11)$$

2.2 SPMC and PI Controllers' Design

In the developed system, there are two controllers used; SPMC and PI controllers. The power flow in the DC-link is carefully regulated using Supplementary Power Modulation Controller (SPMC). The actual frequency control is achieved using PI controllers designed in decentralized pattern.

SPMC Controller Design

The SPMC, shown in Figure 1 is modelled by using the deviations in the frequencies of the CAs, and AC tie line power. It generates a signal, λ_{DC} which controls the power flow through the DC Link. It is designed using (17),

$$\lambda_{DC} = 2\pi K_i^f f_i + K_{ACi} P_{AC_i}^{tie} + 2\pi K_j^f f_j \quad (17)$$

Where K_i^f, K_j^f and K_{AC} are the controller gains which corresponds to the gains for frequency deviations in ith and jth control areas and AC tie-line respectively. The gains are optimized in order to obtain optimal responses from the DC link as well as the entire system.

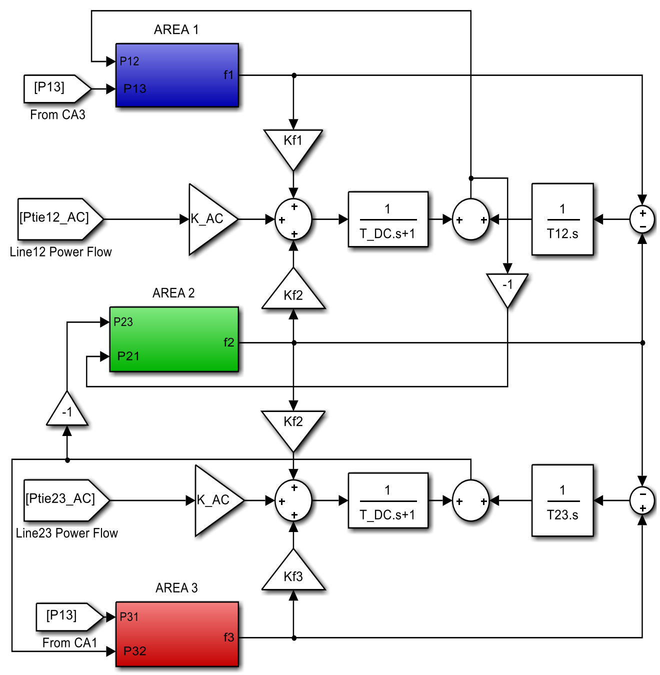

Figure 1: SPMC Implemented in MATLAB

PI Controllers Design and Tuning

To design the LFC Supplementary Controller, a PI controller is designed. The gains of the PI controllers are optimized using QOWOA. The optimization is based on the Integral Square Error (ISE) criteria as shown in (18).

$$min(J_i) \text{ Such that,}$$

$$J_i = \int_0^t (ACE_i)^2; \quad i = 1, 2, 3 \quad (18)$$

Where ACE is the area control error defined in (18).

Controllers designed on the basis of ISE criterion provides reduction of rise time to limit the effect of large initial errors, reduction of peak overshoot and reduction of settling time to limit the effect of small errors lasting for a long time. Further, this criterion is often of practical significance because of the minimization of control effort, but the controller designed on the basis of ISE criterion tends to show a rapid decrease in the large initial error.

Table 1: Optimized Gains of SPMC and PI Controllers

Control Area	Optimized Values	
	$\boldsymbol{K_{AC}}$	$\boldsymbol{K^f}$
1	10.485	0.5992
2	5.733	0.8320
3	6.304	0.8995

3. Simulation Result

The efficacy of the proposed algorithm, the developed multi-area system is implemented and simulated in MATLAB (R2020a) environment. The system is perturbed with 0.5*pu* step-load variation. The responses of the frequency and tie-line powers are then studied and compared with its AC-interconnected counterpart.

Table 2: System Parameters

Component	Parameter	Control Area 1	2	3
Generator	T_g (*sec*)	0.06	0.6	0.6
	T_t (*sec*)	0.32	0.31	0.30
	R (*Hz/pu*)	2.4	2.45	2.5
Power System	T_p (*sec*)	20	25	23
	K_p (*Hz/pu*)	102	103	102
	β_i	.425	0.408	.39
	$T_{ij}^0\ \forall i,j: i \neq j$	.245		

3.1 Responses in Frequency Deviation

In the first instance, the three areas were interconnected with conventional AC tie-line and then subjected with the step load change. The responses of the system are studied. Subsequently, the AC tie-lines are then replaced with the proposed optimized HVDC lines. Similarly, the system responses are studied following the disturbance. The responses of the frequency deviations are shown in Figure 2–4.

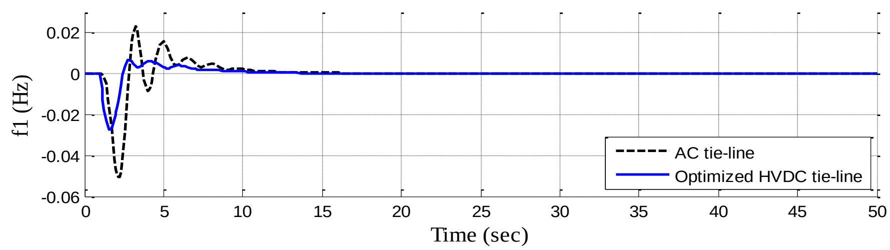

Figure 2: Δf_1 due to load change in area 1

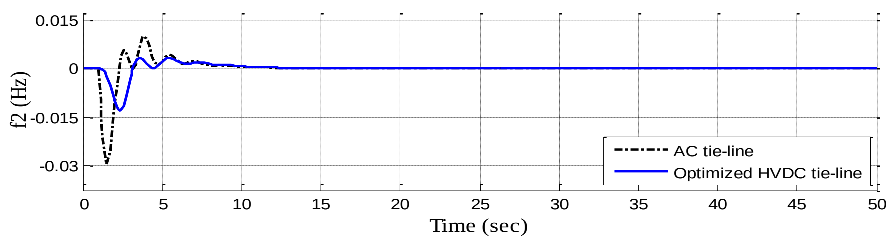

Figure 3: Δf_2 due to load change in area 1

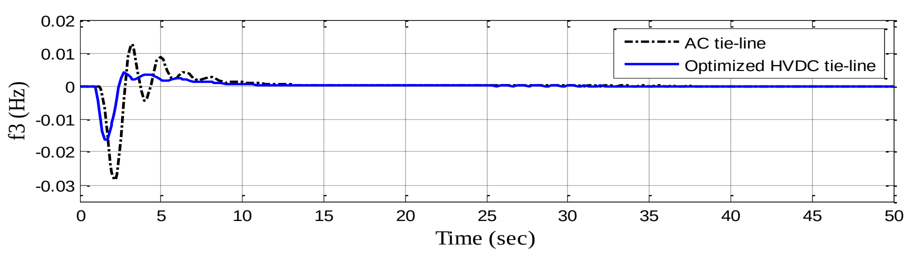

Figure 4: Δf_3 due to load change in area 1

In all the scenarios, the overshoot, settling times and Integral Square Error (ISE) are used as performance metrics to quantify the improvements. Table 1 and 2 summarize the maximum overshoot and settling times of the frequency deviations of system respectively.

Moreover, the improvement is obtained not only in the frequency response, but also the tie-line power deviations, as shown in Figure 5 – 7.

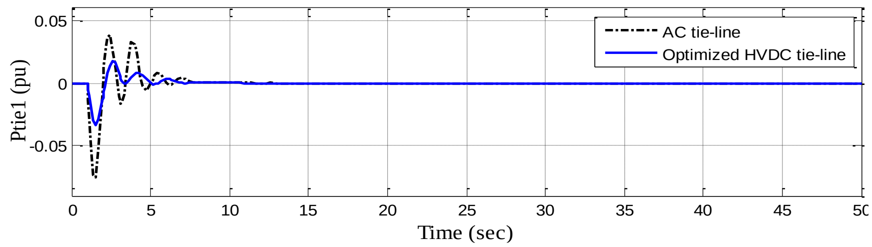

Figure 5: P_1^{tie} due to load change in area 1

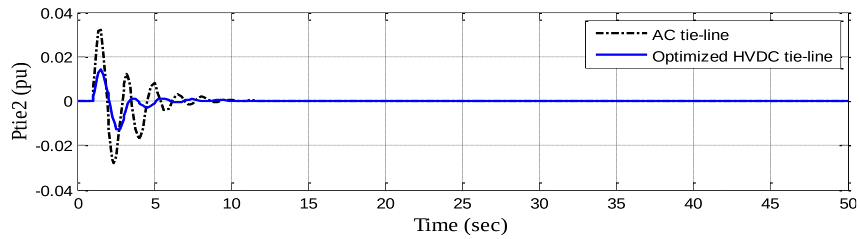

Figure 6: P_2^{tie} due to load change in area 1

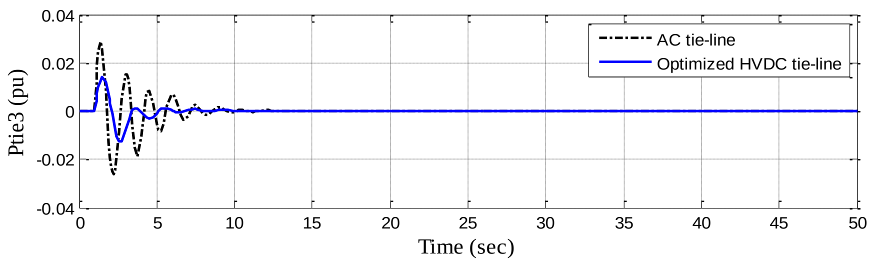

Figure 7: P_3^{tie} following Single Area Step Load Change

Table 3: Overshoots of frequency deviations

Control Area	Overshoot of Frequency deviations (Hz)		% Improvements
	AC Tie-line	Proposed	
1	-0.051	-0.025	50.98%
2	-0.0298	-0.0148	47.14%
3	-0.027	-0.016	40.74%

Table 4: Settling times of frequency deviations

Control Area	Settling Times of Frequency deviations (*sec*)		% Improvements
	AC Tie-line	Proposed	
1	6.20	3.20	48.42%
2	6.83	3.91	42.77%
3	5.92	3.72	36.96%

It can be deduced from the frequency deviation responses that the proposed QOWOA-tuned, HDVC-linked has faster response time and shorter overshoot compared to the similar system linked with AC line.

In all the scenarios, maximum overshoot and settling times are used as performance metrics to quantify the improvements. Table 5 and 6 summarize the maximum overshoot and settling times of the tie-line power deviations of system.

Table 5 Overshoots of tie-line power deviations

Control Area	Overshoot of Tie-line Power (*pu*)		% Improvements
	AC Tie-line	Proposed	
1	-0.065	-0.034	47.98%
2	0.032	0.0176	45.64%
3	0.031	0.0184	40.88%

Table 5: Settling times of tie-line power deviations

Control Area	Settling Times of freq. deviations (*sec*)		% Improvements
	AC Tie-line	Proposed	
1	8.42	4.7145	44.01%
2	13.36	8.1662	38.88%
3	10.89	7.2372	33.60%

It can be deduced from the frequency deviation responses that the proposed WOA-tuned, HDVC-linked has faster response time and shorter overshoot compared to the similar system linked with AC line.

4. Conclusion

This paper presents the development of LFC scheme of a three control area with HVDC-link. Each of the three control areas were equipped with PI controller which were optimized using quasi- oppositional whale optimization algorithm. The optimization was based on the integral square error (ISE). A supplementary power modulation controller (SPMC) was employed to control the flow of DC power in the system. The three area were firstly interconnected with conventional AC line and then subjected with step load. The system responses were studied. A DC link was then introduced to the system. Similarly the system responses were studied. The systems in both cases were implemented and simulated in MATLAB (R 2020b) environment. The performances of the proposed QOWOA-tuned HVDC-linked LFC is compared with that of conventional AC using settling time and maximum deviation as performance metrics. Using HVDC interconnect system, frequency fluctuations, tie line power deviations and ACEs have shorter settling times and smaller overshoots than traditional AC systems. Further the LFC and SPMC parameter are optimized using QOWOA resulting in significant improvement over AC-linked system.

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