

Research Article

New Families of Third-Order Iterative Methods for Finding Multiple Roots

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Two families of third-order iterative methods for finding multiple roots of nonlinear equations are developed in this paper. Mild conditions are given to assure the cubic convergence of two iteration schemes (I) and (II). The presented families include many third-order methods for finding multiple roots, such as the known Dong's methods and Neta's method. Some new concrete iterative methods are provided. Each member of the two families requires two evaluations of the function and one of its first derivative per iteration. All these methods require the knowledge of the multiplicity. The obtained methods are also compared in their performance with various other iteration methods via numerical examples, and it is observed that these have better performance than the modified Newton method, and demonstrate at least equal performance to iterative methods of the same order.

1. Introduction

Finding the roots of nonlinear equations is one of the most important problems in numerical analysis. In this study, we use iterative methods to find a multiple root x^* of multiplicity m ($m > 1$); that is, $f^{(j)}(x^*) = 0$, $j = 0, 1, \dots, m - 1$, and $f^{(m)}(x^*) \neq 0$, of a nonlinear equation $f(x) = 0$.

It is known that the modified Newton method for multiple roots is given by

$$x_{n+1} = x_n - m \frac{f(x_n)}{f'(x_n)}, \quad (1)$$

which converges quadratically [1].

There exists a cubically convergent method for multiple roots, presented by Hansen and Patrick [2]. Consider

$$x_{n+1} = x_n - (f(x_n)) \times \left(\frac{m+1}{2m} f'(x_n) - \frac{f(x_n)f''(x_n)}{2f'(x_n)^2} \right)^{-1}, \quad (2)$$

which is an extension of the classical Halley method of the third order.

Another cubically convergent method for multiple roots is proposed by Traub [3]. Consider

$$x_{n+1} = x_n - \frac{m(3-m)}{2} \frac{f(x_n)}{f'(x_n)} - \frac{m^2}{2} \frac{f(x_n)^2 f''(x_n)}{f'(x_n)^3}, \quad (3)$$

which is an extension of the well-known Chebyshev method of the third order.

In recent years, a lot of methods for multiple roots have been presented and analyzed, which require the knowledge of the multiplicity m ; see [4–24] and references therein.

Based on King's fourth-order method (for simple roots) [25], Dong [4] has developed two third-order methods for

multiple roots, requiring two evaluations of the function and one of its first derivative. Consider

$$\begin{aligned}
 y_n &= x_n - \sqrt{m} \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - m \left(1 - \frac{1}{\sqrt{m}}\right)^{(1-m)} \frac{f(y_n)}{f'(x_n)}, \\
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - \frac{f(y_n)}{((m-1)/m)^{m-1} f(x_n) - f(y_n)} \frac{f(x_n)}{f'(x_n)}.
 \end{aligned}
 \tag{4}$$

Using the same information, Victory Jr. and Neta [5] have developed a third method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - \frac{f(y_n)}{f'(x_n)} \frac{f(x_n) + Af(y_n)}{f(x_n) + Bf(y_n)},
 \end{aligned}
 \tag{6}$$

where

$$\begin{aligned}
 A &= \left(\frac{m}{m-1}\right)^{2m} - \left(\frac{m}{m-1}\right)^{m+1}, \\
 B &= -\frac{(m/(m-1))^m (m-2)(m-1) + 1}{(m-1)^2}.
 \end{aligned}
 \tag{7}$$

Neta [9] has developed another third-order method requiring the same information

$$\begin{aligned}
 y_n &= x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - \frac{(\beta - \alpha) f(x_n) + \gamma f(y_n)}{f'(x_n)},
 \end{aligned}
 \tag{8}$$

where

$$\begin{aligned}
 \alpha &= \frac{1}{2} \frac{m(m+3)}{m+1}, \quad \beta = \frac{m^3 + 4m^2 + 9m + 2}{(m+3)^2}, \\
 \gamma &= \frac{2^{m+1}(m^2 - 1)}{(m+3)^2((m-1)/(m+1))^m}.
 \end{aligned}
 \tag{9}$$

Based on Halley's method, Li et al. [15] have proposed a family of third methods using the same information. Consider

$$\begin{aligned}
 y_n &= x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= x_n - \frac{m\alpha^2 \mu^m f(x_n)}{(m - \alpha + \alpha^2) \mu^m f(x_n) - (m - \alpha) f(y_n)} \frac{f(x_n)}{f'(x_n)},
 \end{aligned}
 \tag{10}$$

where α is a real parameter and $\alpha \neq 0, m$, and $\mu = (m - \alpha)/m$.

Note also that, based on Traub's method [2], Homeier [16] has suggested a family of third methods using the same information. Consider

$$\begin{aligned}
 y_n &= x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= x_n - \beta \frac{f(x_n)}{f'(x_n)} - \frac{f(y_n)}{\gamma f'(x_n)},
 \end{aligned}
 \tag{11}$$

where $\alpha \neq 0, m$ is a real parameter, $\beta = (m/\alpha^2)(\alpha^2 + \alpha - m)$, and $\gamma = (1/m)(1 - \alpha/m)^m(\alpha^2/(m - \alpha))$.

In this paper, we propose two new families of third-order methods for multiple roots; each of the methods requires two-function and one-derivative evaluation per iteration, respectively. The presented methods are obtained by investigating the following two iteration schemes:

$$\text{(I)} \begin{cases} y_n = x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \\ x_{n+1} = y_n - \frac{af(x_n) + bf(y_n)}{cf(x_n) + df(y_n)} \frac{f(y_n)}{f'(x_n)}, \end{cases}
 \tag{12}$$

$$\text{(II)} \begin{cases} y_n = x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \\ x_{n+1} = y_n - \frac{af(x_n) + bf(y_n)}{cf(x_n) + df(y_n)} \frac{f(x_n)}{f'(x_n)}, \end{cases}
 \tag{13}$$

where α, a, b, c , and d are parameters to be determined. By specially choosing the parameters in (12) and (13), we get two new families of third-order methods, which include methods (4)–(6), (8), (10), and (11). In fact, the mild conditions to assure the cubic convergence of (I)-type iteration (12) or (II)-type iteration (13) are given. Divided differences are adopted successfully in developing our methods, which will be useful in developing more new methods. Finally, we use some numerical examples to compare the presented methods with the modified Newton method and some known third-order methods.

2. Preliminaries

We need the definitions of divided differences and their properties.

Definition 1 (see [26]). The divided differences $f[a_0, a_1, \dots, a_k]$ on $k+1$ distinct points a_0, a_1, \dots, a_k of a function $f(x)$ are defined by

$$\begin{aligned}
 f[a_0] &= f(a_0), \\
 f[a_0, a_1] &= \frac{f[a_0] - f[a_1]}{a_0 - a_1}, \\
 &\vdots \\
 f[a_0, a_1, \dots, a_k] &= \frac{f[a_0, a_1, \dots, a_{k-1}] - f[a_1, a_2, \dots, a_k]}{a_0 - a_k}.
 \end{aligned}
 \tag{14}$$

If the function f is sufficiently differentiable, then its divided differences $f[a_0, a_1, \dots, a_k]$ can be defined if some of the arguments a_i coincide. For instance, if $f(x)$ has a derivative of the k th order at a_0 , then it makes sense to define

$$f \left[\underbrace{a_0, a_0, \dots, a_0}_{k+1} \right] = \frac{f^{(k)}(a_0)}{k!}. \tag{15}$$

Lemma 2 (see [26]). *The divided differences $f[a_0, a_1, \dots, a_k]$ are symmetric functions of their arguments; that is, they are invariant to permutations of the a_0, a_1, \dots, a_k .*

Lemma 3 (see [26]). *If the function f has $(k + 1)$ st derivative, then, for every argument x , the following interpolation formula holds:*

$$f(x) = f[a_0] + \sum_{i=1}^k f[a_0, a_1, \dots, a_i] \prod_{j=0}^{i-1} (x - a_j) + f[a_0, a_1, \dots, a_k, x] \prod_{i=0}^k (x - a_i). \tag{16}$$

Lemma 4. *If the function f has a derivative of the $(m + 1)$ th order, and x^* is a multiple root of multiplicity m , then, for every argument x , the following formulae hold:*

$$f(x) = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, x \right] (x - x^*)^m, \tag{17}$$

$$f'(x) = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, x, x \right] (x - x^*)^m + mf \left[\underbrace{x^*, x^*, \dots, x^*}_m, x \right] (x - x^*)^{m-1}. \tag{18}$$

Proof. Applying Lemma 3 to the case of the multiple zero x^* of multiplicity m and using (15), we get (17). Differentiating both sides of (17) gives (18). \square

3. Development of New Families of Third-Order Methods

We would like to find the five parameters α, a, b, c , and d in I-type iteration (12) and II-type iteration (13) so as to maximize its order of convergence to a root x^* of multiplicity m , respectively. Let e_n, d_n be the errors at the n th step; that is,

$$e_n = x_n - x^*, \quad d_n = y_n - x^*. \tag{19}$$

Define functions $g(x)$ and $h(x)$ as follows:

$$g(x) = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, x \right], \tag{20}$$

$$h(x) = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, x, x \right].$$

Write

$$g_n = g(x_n), \quad h_n = h(x_n), \quad g_* = g(x^*), \tag{21}$$

$$h_* = h(x^*).$$

In view of (17) and (18), we get the following:

$$f(x_n) = g_n e_n^m, \tag{22}$$

$$f'(x_n) = h_n e_n^m + m g_n e_n^{m-1}, \tag{23}$$

$$f(y_n) = g(y_n) d_n^m. \tag{24}$$

Using the definitions of divided differences, we get the following:

$$g(y_n) = g(y_n) - g(x_n) + g(x_n) = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, y_n, x_n \right] (d_n - e_n) + g_n = \left(f \left[\underbrace{x^*, x^*, \dots, x^*}_m, y_n, x_n \right] - h(x_n) + h(x_n) \right) \times (d_n - e_n) + g_n = p_n (d_n - e_n)^2 + h_n (d_n - e_n) + g_n, \tag{25}$$

where

$$p_n = f \left[\underbrace{x^*, x^*, \dots, x^*}_m, y_n, x_n, x_n \right]. \tag{26}$$

In view of (22), (23), (12), and (13), we get in turn

$$\frac{f(x_n)}{f'(x_n)} = \frac{g_n e_n}{h_n e_n + m g_n}, \tag{27}$$

$$d_n = e_n - \alpha \frac{g_n e_n}{h_n e_n + m g_n} = \frac{h_n e_n + (m - \alpha) g_n}{h_n e_n + m g_n} e_n, \tag{28}$$

$$d_n - e_n = - \frac{\alpha g_n e_n}{h_n e_n + m g_n}. \tag{29}$$

Substituting (29) into (25) yields

$$g(y_n) = p_n \left(- \frac{\alpha g_n e_n}{h_n e_n + m g_n} \right)^2 + h_n \left(- \frac{\alpha g_n e_n}{h_n e_n + m g_n} \right) + g_n = \frac{g_n}{(h_n e_n + m g_n)^2} \left([\alpha^2 p_n g_n + (1 - \alpha) h_n^2] e_n^2 + (2 - \alpha) m h_n g_n e_n + m^2 g_n^2 \right). \tag{30}$$

Substituting (30) and (28) into (24) leads to

$$f(y_n) = \frac{g_n [h_n e_n + (m - \alpha) g_n]^m}{(h_n e_n + m g_n)^{m+2}} \times \left([\alpha^2 p_n g_n + (1 - \alpha) h_n^2] e_n^2 + (2 - \alpha) m h_n g_n e_n + m^2 g_n^2 \right) e_n^m. \tag{31}$$

Write

$$A_n = h_n e_n + m g_n,$$

$$B_n = h_n e_n + (m - \alpha) g_n,$$

$$C_n = [\alpha^2 p_n g_n + (1 - \alpha) h_n^2] e_n^2 + (2 - \alpha) m h_n g_n e_n + m^2 g_n^2. \quad (32)$$

Using (23), (24), and (32), we get

$$\begin{aligned} f'(x_n) &= A_n e_n^{m-1}, \\ f(y_n) &= \frac{g_n B_n^m C_n}{A_n^{m+2}} e_n^m. \end{aligned} \quad (33)$$

Then, we can get the error equations as follows:

$$\begin{aligned} e_{n+1} &= \frac{B_n}{A_n} e_n - \frac{a g_n e_n^m + b (g_n B_n^m C_n / A_n^{m+2}) e_n^m}{c g_n e_n^m + d (g_n B_n^m C_n / A_n^{m+2}) e_n^m} \\ &\quad \times \frac{(g_n B_n^m C_n / A_n^{m+2}) e_n^m}{A_n e_n^{m-1}} \\ &= - \left((a A_n^{m+2} + b B_n^m C_n) g_n B_n^{m-1} C_n \right. \\ &\quad \left. - (c A_n^{m+2} + d B_n^m C_n) A_n^{m+2} \right) B_n e_n \\ &\quad \times \left((c A_n^{m+2} + d B_n^m C_n) A_n^{m+3} \right)^{-1}, \end{aligned} \quad (34)$$

for I-type iteration (12), and

$$\begin{aligned} e_{n+1} &= \frac{B_n}{A_n} e_n - \frac{a g_n e_n^m + b (g_n B_n^m C_n / A_n^{m+2}) e_n^m}{c g_n e_n^m + d (g_n B_n^m C_n / A_n^{m+2}) e_n^m} \\ &\quad \times \frac{g_n e_n^m}{A_n e_n^{m-1}} \\ &= - \left((a A_n^{m+2} + b B_n^m C_n) g_n - (c A_n^{m+2} + d B_n^m C_n) B_n \right) e_n \\ &\quad \times \left((c A_n^{m+2} + d B_n^m C_n) A_n \right)^{-1}, \end{aligned} \quad (35)$$

for II-type iteration (13).

In view of (34) and (35), the order of convergence for I-type or II-type iteration will arrive at three provided that

$$\frac{\Phi_n}{(c A_n^{m+2} + d B_n^m C_n) A_n^{m+3}} = O(e_n^2), \quad (36)$$

or

$$\frac{\Psi_n}{(c A_n^{m+2} + d B_n^m C_n) A_n} = O(e_n^2), \quad (37)$$

holds true, respectively. Here

$$\begin{aligned} \Phi_n &= \left[(a A_n^{m+2} + b B_n^m C_n) g_n B_n^{m-1} C_n \right. \\ &\quad \left. - (c A_n^{m+2} + d B_n^m C_n) A_n^{m+2} \right] B_n, \end{aligned} \quad (38)$$

$$\Psi_n = (a A_n^{m+2} + b B_n^m C_n) g_n - (c A_n^{m+2} + d B_n^m C_n) B_n.$$

Write

$$\lambda = m - \alpha. \quad (39)$$

In view of (32), we can get, as $n \rightarrow \infty$,

$$\begin{aligned} A_n &\rightarrow m g_* = m f \left[\frac{x^*, x^*, \dots, x^*}{m+1} \right] = m \frac{f^{(m)}(x^*)}{m!} \neq 0, \\ B_n &\rightarrow \lambda g_*, \\ C_n &\rightarrow (m g_*)^2, \end{aligned} \quad (40)$$

and then

$$\begin{aligned} (c A_n^{m+2} + d B_n^m C_n) A_n^{m+3} &\rightarrow (c m^m + d \lambda^m) m^{m+5} g_*^{2m+5}, \\ &\quad (n \rightarrow \infty), \\ (c A_n^{m+2} + d B_n^m C_n) A_n &\rightarrow (c m^m + d \lambda^m) m^3 g_*^{m+3}, \\ &\quad (n \rightarrow \infty), \end{aligned} \quad (41)$$

which show that, in order to assure the denominators in (36) and (37) are not equal to zero, we demand naturally that

$$c m^m + d \lambda^m \neq 0. \quad (42)$$

It is obvious that, under the condition (42), the error relations (36) and (37) are equivalent to

$$\Phi_n = O(e_n^2), \quad (43)$$

$$\Psi_n = O(e_n^2), \quad (44)$$

respectively.

Next we will find conditions to assure (43) and (44). Note that the factor B_n of Φ_n plays an important role on the order of Φ_n . In fact, using the Taylor formula, we get from (32) the following:

$$B_n = \lambda g_* + O(e_n). \quad (45)$$

Then, in the case $\lambda = 0$, to assure the relation (43) holds true, the following estimate is needed:

$$\begin{aligned} \Delta_n &= (a A_n^{m+2} + b B_n^m C_n) g_n B_n^{m-1} C_n \\ &\quad - (c A_n^{m+2} + d B_n^m C_n) A_n^{m+2} = O(e_n), \end{aligned} \quad (46)$$

which demands

$$\Delta_n \rightarrow -c (m g_*)^{2m+4} = 0, \quad (n \rightarrow \infty); \quad (47)$$

that is, $c = 0$. This is a contradiction to (42). Hence, in the case $\lambda = 0$, the relation (43) cannot be satisfied; that is, we cannot choose parameters so that the order of convergence of (I)-type iteration (12) arrives at three.

In what follows, we suppose $\lambda \neq 0$. In this case, $B_n \rightarrow \lambda g_* \neq 0 (n \rightarrow \infty)$, and then (43) is equivalent to

$$\Delta_n = O(e_n^2). \tag{48}$$

In view of (32), and by a straight computation, we can get

$$\Delta_n = u_n + v_n e_n + O(e_n^2), \tag{49}$$

where

$$u_n = (m^m \lambda^{m-1} a + \lambda^{2m-1} b - m^{2m} c - m^m \lambda^m d) m^4 g_n^{2m+4}, \tag{50}$$

$$\begin{aligned} v_n = & (m^m \lambda^{m-2} [\lambda^2 + 4\lambda + m(m-1)] a \\ & + \lambda^{2m-2} [2\lambda^2 + (4-2m)\lambda + m(2m-1)] b \\ & - (2m+4) m^{2m} c \\ & - m^m \lambda^{m-1} (\lambda^2 + 4\lambda + m^2) d) m^3 g_n^{2m+3} h_n. \end{aligned} \tag{51}$$

In view of (49) and in order to assure the relation (48) holds, we should choose parameters $\lambda, a, b, c,$ and d such that

$$\begin{aligned} m^m \lambda^{m-1} a + \lambda^{2m-1} b - m^{2m} c - m^m \lambda^m d = 0, \\ m^m \lambda^{m-2} [\lambda^2 + 4\lambda + m(m-1)] a \\ + \lambda^{2m-2} [2\lambda^2 + (4-2m)\lambda + m(2m-1)] b \\ - (2m+4) m^{2m} c - m^m \lambda^{m-1} (\lambda^2 + 4\lambda + m^2) d = 0. \end{aligned} \tag{52}$$

By a straight computation, we deduce that

$$c = \frac{m^{m+1} \lambda^{m-1} a + [m - (\lambda - m)^2] \lambda^{2m-1} b}{(\lambda - m)^2 m^{2m}}, \tag{53}$$

$$d = \frac{[(\lambda - m)^2 - m] m^m a + [2(\lambda - m)^2 - m] \lambda^m b}{\lambda(\lambda - m)^2 m^m}. \tag{54}$$

Substituting (53) and (54) into the left side of (42), we get

$$\begin{aligned} & cm^m + d\lambda^m \\ &= \frac{m^{m+1} \lambda^{m-1} a + [m - (\lambda - m)^2] \lambda^{2m-1} b}{(\lambda - m)^2 m^m} \\ &+ \frac{[(\lambda - m)^2 - m] m^m \lambda^{m-1} a + [2(\lambda - m)^2 - m] \lambda^{2m-1} b}{(\lambda - m)^2 m^m} \\ &= \frac{m^m a + \lambda^m b}{m^m} \lambda^{m-1}, \end{aligned} \tag{55}$$

which shows the condition (42) is equivalent to

$$am^m + b(m - \alpha)^m \neq 0. \tag{56}$$

We summarize our development of new methods done so far in the following theorem.

Theorem 5. Let $x^* \in I$ be a multiple root of multiplicity $m (m > 1)$ of a sufficiently differentiable function $f : I \rightarrow \mathbb{R}$ for an open interval I . If x_0 is sufficiently close to x^* , then the methods defined by (I)-type iteration (12) are cubically convergent for any parameters $\alpha, a, b, c,$ and d such that $\alpha \neq 0$ and (53), (54), and (56) hold.

Next, we turn to find the proper conditions to establish the relation (44). In view of (32), and by a straight computation, we can get

$$\Psi_n = r_n + s_n e_n + O(e_n^2), \tag{57}$$

where

$$\begin{aligned} r_n = & (m^m a + \lambda^m b - m^m \lambda c - \lambda^{m+1} d) m^2 g_n^{m+3}, \\ s_n = & ((m+2) m^{m+1} a + [(2-\alpha) m \lambda^m + m^3 \lambda^{m-1}] b \\ & - [m^{m+2} + m^{m+1} (m+2) \lambda] c \\ & - [(2-\alpha) m \lambda^{m+1} + m^2 (m+1) \lambda^m] d) g_n^{m+2} h_n. \end{aligned} \tag{58}$$

In view of (57) and in order to assure the relation (44) holds, we should choose parameters $\lambda, a, b, c,$ and d such that

$$\begin{aligned} m^m a + \lambda^m b - m^m \lambda c - \lambda^{m+1} d = 0, \\ (m+2) m^m a + [(2-\alpha) \lambda + m^2] \lambda^{m-1} b \\ - [m + (m+2) \lambda] m^m c \\ - [(2-\alpha) \lambda + m(m+1)] \lambda^m d = 0. \end{aligned} \tag{59}$$

By a straight computation, we deduce that

$$\begin{aligned} c = & \frac{[(\lambda - m)^2 + m] m^{m-1} a + \lambda^m b}{\lambda(\lambda - m)^2 m^{m-1}}, \\ d = & \frac{-m^{m+1} a + [(\lambda - m)^2 - m] \lambda^m b}{\lambda^{m+1} (\lambda - m)^2}. \end{aligned} \tag{60}$$

Substituting (60) into the left side of (42), we get

$$cm^m + d\lambda^m = \frac{m^m a + \lambda^m b}{\lambda}, \tag{61}$$

which shows the condition (42) is also equivalent to the condition given by (56).

We can summarize the development of new methods involving (II)-type iteration (13) done so far in the following theorem.

Theorem 6. Let $x^* \in I$ be a multiple root of multiplicity $m (m > 1)$ of a sufficiently differentiable function $f : I \rightarrow \mathbb{R}$ for an open interval I . If x_0 is sufficiently close to x^* , then the methods defined by (II)-type iteration (13) are cubically convergent for any parameters $\alpha, a, b, c,$ and d such that $\alpha \neq 0$ and (60) and (56) hold.

Choosing $\alpha = \sqrt{m}$, $a = 1$, and $b = 0$, we can deduce from (53), (54), and (56) that

$$c = \frac{(m - \sqrt{m})^{m-1}}{m^m}, \tag{62}$$

$$d = 0, \tag{63}$$

$$am^m + b(m - \alpha)^m = m^m \neq 0. \tag{64}$$

Using the parameters α , a , b , c , and d given above in (I)-type iteration (12), we can obtain Dong’s method (4), and its order of convergence arrives at three by Theorem 5.

Choosing $\alpha = 1$, $a = 1$, and $b = 0$, we can deduce from (53), (54), and (56) that

$$c = \frac{(m - 1)^{m-1}}{m^{m-1}}, \tag{65}$$

$$d = -1,$$

$$am^m + b(m - \alpha)^m = m^m \neq 0.$$

Using the parameters α , a , b , c , and d given above in (I)-type iteration (12), we can obtain Dong’s method (5), and its order of convergence arrives at three by Theorem 5.

Choosing $\alpha = 1$, $a = 1$, and $b = (m/(m - 1))^{2m} - (m/(m - 1))^{m+1}$, we can deduce from (53), (54), and (56) that

$$c = 1, \tag{66}$$

$$d = -\frac{(m/(m - 1))^m (m - 2) (m - 1) + 1}{(m - 1)^2}, \tag{67}$$

$$am^m + b(m - \alpha)^m = m^m \left[1 + \left(\frac{m}{m - 1} \right)^m - \frac{m}{m - 1} \right] \neq 0. \tag{68}$$

Using the parameters α , a , b , c , and d given above in (I)-type iteration (12), we can obtain Victory and Neta’s method (6), and its order of convergence arrives at three by Theorem 5.

Let $\alpha = (1/2)(m(m + 3)/(m + 1))$, $a = (m^3 + 4m^2 + 9m + 2)/(m + 3)^2 - (1/2)(m(m + 3)/(m + 1))$, $b = 2^{m+1}(m^2 - 1)/(m + 3)^2((m - 1)/(m + 1))^m$, $c = 0$, and $d = 1$. Using the definition of λ , we get

$$\lambda = \frac{m(m - 1)}{2(m + 1)}. \tag{69}$$

We can verify that the parameters given above satisfy (52), and thus they also satisfy (53) and (54) (as c given in (53) and d given in (54) are solved from (52)). Furthermore, it is easy to verify that the condition (42) holds:

$$cm^m + d\lambda^m = \left(\frac{m(m - 1)}{2(m + 1)} \right)^m \neq 0. \tag{70}$$

This means that the condition (56) is also true, since (56) is equivalent to (42). Using the parameters α , a , b , c , and d given in (I)-type iteration (12), we can obtain Neta’s method (8), and its order of convergence arrives at three by Theorem 5.

We can verify that the family of methods (11) given by Homeier [16] satisfies all conditions in Theorem 5. First, we can rewrite (11) as follows:

$$y_n = x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \tag{71}$$

$$x_{n+1} = y_n - \frac{(\beta - \alpha) f(x_n) + (1/\gamma) f(y_n)}{f(y_n)} \frac{f(y_n)}{f'(x_n)},$$

where $\alpha \neq 0$, m is a real parameter, $\beta = (m/\alpha^2)(\alpha^2 + (\alpha - m)) = (m/\alpha^2)(\alpha^2 - \lambda)$, and $\gamma = (1/m)(1 - \alpha/m)^m(\alpha^2/(m - \alpha)) = (\lambda^{m-1}\alpha^2/m^{m+1})$. Choosing $a = \beta - \alpha$ and $b = 1/\gamma$, we can deduce from (53), (54), and (56) that $c = 0$, $d = 1$, and

$$cm^m + d\lambda^m = (m - \alpha)^m \neq 0. \tag{72}$$

This means that the condition (56) is also true. Using the parameters α , a , b , c , and d given in (I)-type iteration (12), we can obtain Homeier’s family of methods (11), which has cubic convergence by Theorem 5.

We can verify that the family of methods (10) given by Homeier [16] satisfies all conditions in Theorem 6. First, we can rewrite (10) as follows:

$$y_n = x_n - \alpha \frac{f(x_n)}{f'(x_n)}, \tag{73}$$

$$x_{n+1} = y_n - \left((m\alpha^2 - m\alpha + \alpha^2 - \alpha^3) \right. \\ \left. \times \mu^m f(x_n) + \alpha(m - \alpha) f(y_n) \right) \\ \times \left((m - \alpha + \alpha^2) \mu^m f(x_n) - (m - \alpha) f(y_n) \right)^{-1} \\ \times \frac{f(x_n)}{f'(x_n)}, \tag{74}$$

where α is a real parameter and $\alpha \neq 0$, m , and $\mu = (m - \alpha)/m$.

Let $a = \lambda^{m+1}\alpha(\alpha - 1)/m^m$, $b = \alpha\lambda$, $c = (\lambda + \alpha^2)\lambda^m/m^m$, and $d = -\lambda$. We can verify that the parameters given above satisfy (60) and (56). Using the parameters α , a , b , c , and d given in (II)-type iteration (13), we can obtain Shengguo et al.’s family of methods (10), which has cubic convergence by Theorem 6.

4. Some Concrete Methods

In this section, we give some concrete iterative forms of (I)-type iteration (12) and (II)-type iteration (13).

Method 1. Choosing $\alpha = 1$, $a = 0$, and $b = 1$, we obtain from (63) and (64) that $c = ((m - 1)/m)^{2m}$, $d = (2 - m)(m - 1)^{m-1}/m^m$, and $am^m + b(m - \alpha)^m = (m - 1)^m \neq 0$.

Using these parameters in (12), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - (f(y_n)) \times \left(\left(\frac{m-1}{m} \right)^{2m} f(x_n) \right. \\
 &\quad \left. + \frac{(2-m)(m-1)^{m-1}}{m^m} f(y_n) \right)^{-1} \\
 &\quad \times \frac{f(y_n)}{f'(x_n)},
 \end{aligned} \tag{75}$$

which has cubic convergence by Theorem 5.

Method 2. Choosing $\alpha = 1$, $c = 1$, and $d = 0$, we can obtain from (61) and (62) that $a = (2-m)m^m/(m-1)^{m-1}$, $b = m^{2m}/(m-1)^{2m-2}$, and $cm^m + d(m-\alpha)^m = m^m \neq 0$. Using these parameters in (12), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - \left(\frac{(2-m)m^m}{(m-1)^{m-1}} f(x_n) \right. \\
 &\quad \left. + \frac{m^{2m}}{(m-1)^{2m-2}} f(y_n) \right) \\
 &\quad \times (f(x_n))^{-1} \\
 &\quad \times \frac{f(y_n)}{f'(x_n)},
 \end{aligned} \tag{76}$$

which has cubic convergence by Theorem 5.

Method 3. Choosing $\alpha = 1$, $b = 1$, and $d = 1$, we can obtain from (61) and (62) that $a = ((m-1)^{m-1}(2-m) - m^m)/m^m$, $c = ((m-1)^{2m-2} - m^{m+1}(m-1)^{m-1})/m^{2m}$, and $cm^m + d(m-\alpha)^m = (m-1)^{m-1}[(m-1)^{m-1} - m^m]/m^m \neq 0$. Using these parameters in (12), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - \left(\frac{(m-1)^{m-1}(2-m) - m^m}{m^m} f(x_n) + f(y_n) \right) \\
 &\quad \times \left(\frac{(m-1)^{2m-2} - m^{m+1}(m-1)^{m-1}}{m^{2m}} \right. \\
 &\quad \left. \times f(x_n) + f(y_n) \right)^{-1} \\
 &\quad \times \frac{f(y_n)}{f'(x_n)},
 \end{aligned} \tag{77}$$

which has cubic convergence by Theorem 5.

Method 4. Choosing $\alpha = 1$, $a = 1$, and $b = 0$, we can obtain from (70) and (71) that $c = (m+1)/(m-1)$, $d =$

$-(m/(m-1))^{m+1}$, and $am^m + b(m-\alpha)^m = m^m \neq 0$. Using these parameters in (13), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - (f(x_n)) \\
 &\quad \times \left(\frac{m+1}{m-1} f(x_n) - \left(\frac{m}{m-1} \right)^{m+1} f(y_n) \right)^{-1} \\
 &\quad \times \frac{f(x_n)}{f'(x_n)},
 \end{aligned} \tag{78}$$

which has cubic convergence by Theorem 6.

Method 5. Choosing $\alpha = 1$, $a = 1$, and $c = 0$, we can obtain from (68) and (69) that $b = -(m+1)m^{m-1}/(m-1)^m$, $d = -m^{m-1}/(m-1)^{m+1}$, and $cm^m + d(m-\alpha)^m = -m^{m-1}/(m-1) \neq 0$. Using these parameters in (13), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n + \left(f(x_n) - \frac{(m+1)m^{m-1}}{(m-1)^m} f(y_n) \right) \\
 &\quad \times \left(\frac{m^{m-1}}{(m-1)^{m+1}} f(y_n) \right)^{-1} \\
 &\quad \times \frac{f(x_n)}{f'(x_n)},
 \end{aligned} \tag{79}$$

which has cubic convergence by Theorem 6.

Method 6. Choosing $\alpha = \sqrt{m}$, $a = 1$, and $b = 0$, we can obtain from (70) and (71) that $c = 2/(m-\sqrt{m})$, $d = -m^m/(m-\sqrt{m})^{(m+1)}$, and $am^m + b(m-\alpha)^m = m^m \neq 0$. Using these parameters in (13), we get a new method. Consider

$$\begin{aligned}
 y_n &= x_n - \sqrt{m} \frac{f(x_n)}{f'(x_n)}, \\
 x_{n+1} &= y_n - (f(x_n)) \\
 &\quad \times \left(\frac{2}{m-\sqrt{m}} f(x_n) - \frac{m^m}{(m-\sqrt{m})^{m+1}} f(y_n) \right)^{-1} \\
 &\quad \times \frac{f(x_n)}{f'(x_n)},
 \end{aligned} \tag{80}$$

which has cubic convergence by Theorem 6.

5. Numerical Examples

We employ Method 1 (RM1), (75)–Method 6 (RM6), (80) to solve some nonlinear equations and compare them with the

TABLE 1: Comparison of various iterative methods for the function $f_1(x)$ under the same total number of function evaluations (TNFE) required by all methods.

Method	$ x_n - x^* $	$ f(x_n) $	COC
MNM	$3.92e - 94$	$9.48e - 187$	2.0000000
DM	$4.83e - 117$	$1.44e - 232$	3.0000000
VM	$1.42e - 118$	$1.24e - 235$	3.0000000
RM1	$4.63e - 116$	$1.32e - 230$	3.0000000
RM2	$4.63e - 116$	$1.32e - 230$	3.0000000
RM3	$5.53e - 130$	$1.88e - 258$	3.0000000
RM4	$3.98e - 140$	$9.77e - 279$	3.0000000
RM5	$1.14e - 102$	$7.95e - 204$	3.0000000
RM6	$1.04e - 103$	$6.71e - 206$	3.0000000

TNFE = 12.

TABLE 2: Comparison of various iterative methods for the function $f_2(x)$ under the same total number of function evaluations (TNFE) required by all methods.

Method	$ x_n - x^* $	$ f(x_n) $	COC
MNM	$2.83e - 95$	$1.06e - 283$	2.0000000
DM	$1.88e - 109$	$3.11e - 326$	3.0000000
VM	$3.19e - 107$	$1.52e - 319$	3.0000000
RM1	$2.04e - 106$	$4.00e - 317$	3.0000000
RM2	$2.59e - 104$	$8.11e - 311$	3.0000000
RM3	$8.19e - 110$	$2.57e - 327$	3.0000000
RM4	$2.09e - 113$	$4.27e - 338$	3.0000000
RM5	$4.66e - 100$	$4.73e - 298$	3.0000000
RM6	$1.05e - 144$	$5.39e - 432$	3.0000000

TNFE = 12.

TABLE 3: Comparison of various iterative methods for the function $f_3(x)$ under the same total number of function evaluations (TNFE) required by all methods.

Method	$ x_n - x^* $	$ f(x_n) $	COC
MNM	$1.53e - 119$	$4.09e - 478$	2.0000000
DM	$5.39e - 167$	$6.27e - 668$	3.0000000
VM	$1.91e - 176$	$9.90e - 706$	3.0000000
RM1	$9.39e - 185$	$5.79e - 739$	3.0000000
RM2	$3.08e - 169$	$6.69e - 677$	3.0000000
RM3	$9.92e - 164$	$7.21e - 655$	3.0000000
RM4	$1.38e - 156$	$2.73e - 626$	3.0000000
RM5	$1.84e - 152$	$8.48e - 610$	3.0000000
RM6	$7.89e - 143$	$2.89e - 571$	3.0000000

TNFE = 12.

modified Newton method (MNM), (1), Dong's method (DM), (4), and Victory-Neta's method (VM).

Tables 1, 2, and 3 show the difference of the root x^* and the approximation x_n to x^* for the function $f_1 - f_3$, respectively, where x^* is the exact root computed with 650 significant digits and x_n is calculated by using the same total number of function evaluations (TNFE) for all methods. The absolute values of the function ($|f(x_n)|$) and the computational order

of convergence (COC) are also shown in these tables. Here, COC is defined by [27]

$$\rho \approx \frac{\ln |(x_{n+1} - x^*) / (x_n - x^*)|}{\ln |(x_n - x^*) / (x_{n-1} - x^*)|}. \quad (81)$$

The following functions are used for the comparison:

$$f_1(x) = (\sin^2 x - x^2 + 1)^2,$$

$$x_0 = 1.45,$$

$$x^* \approx 1.4044916482153412260350868178,$$

$$f_2(x) = (\cos x - x)^3,$$

$$x_0 = 0.9,$$

(82)

$$x^* \approx 0.73908513321516064165531208767,$$

$$f_3(x) = (\ln(x) + \sqrt{x} - 5)^4,$$

$$x_0 = 8.0,$$

$$x^* \approx 8.3094326942315717953469556827.$$

As shown in Tables 1, 2, and 3, the presented methods in this contribution are preferable to the modified Newton method by numerical tests. Note also that the presented methods show at least equal performance as compared with some other methods of the same order.

6. Conclusion

In this work, we obtained two families of third-order methods by using new techniques of divided differences for solving nonlinear equations with multiple roots. The proposed methods contain many known methods, such as Dong's methods and Neta's method. We conclude from the numerical examples that the proposed methods have at least equal performance as compared with the other iterative methods of the same order. Moreover, it was observed that these methods have better performance than the modified Newton method. We will continue our study to confirm if some fourth-order methods can be obtained using the same ideas in this contribution.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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